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COMWIN Antenna Project: Final Report FY 1999 to 2002

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ADMINISTRATIVE INFORMATION

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ACKNOWLEDGMENTS

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We would also like to express our profound appreciation to Bob O'Neill who fabricated all the antennas for the COMWIN system. His artistry is exceeded only by his willingness to help. We would also like to thank John Moniz of the Office of Naval Research, Code 353, for providing the support of the effort from FY 2000 through FY 2002.

EXECUTIVE SUMMARY

The two goals of the **COM**bat **W**ear **IN**tegration (COMWIN) project are to develop a soldier-carried antenna that can transmit or receive a signal at any frequency from 2 MHz to 2 GHz and that disguises the identity of the radio operator. The purpose of the first aim is to make the antenna compatible with the hand-held radio that will be manufactured in accordance with the Operational Requirements Document of the Joint Tactical Radio. The purpose of the second aim is to increase the difficulty of snipers to target the radio operators and disrupt command, communications, and control at the squad level. Both aims are achieved by integrating the antenna into the uniform of the soldier or marine.

This document is comprehensive in that it provides a summary of all the important steps taken during the 3-year period of the effort. Details will be provided on the work done during Fiscal Year (FY) 2002.

During FY 1999, Professor Jovan Lebaric of the Naval Postgraduate School formed the basic concept of the COMWIN antenna system. His search of the literature and calculations determined that no antenna could be efficient over the full frequency range of 2 MHz to 2 GHz. No fewer than three antennas would be needed. He thought that by covering the torso a vest antenna could handle the 30- to 500-MHz frequency range. An antenna conformal to the helmet could handle the 500- to 2000-MHz range. Finally, an antenna that used the whole body and the ground to complete the circuit could possibly be efficient over the 2- to 30-MHz range. He also coined the acronym, COMWIN. The SPAWAR Systems Center, San Diego (SSC San Diego) Model Shop fabricated the initial model of the vest antenna, called the Mark I.[1] Impedance, gain, and patterns of the Mark I were measured at the SSC San Diego Model Range during August and September 1999. The measurements validated the calculations by Lebaric on impedance and patterns.

Initial measurements of the impedance indicated that a 2:1 transformer would provide a good match for the 100- to 500-MHz frequency range. By good match, we mean that the voltage standing wave ratio (VSWR) is less than 3:1.[2] The Mark I vest antenna on a Styrofoam mannequin had a VSWR less than 3.1:1 for frequencies between 100 and 500 MHz. The gain of the Mark 1 was between 2 and 6 dBi in this frequency range. Lebaric suggested that making the gap into a saw-tooth pattern would lengthen the path of the signal and provide better matching for the militarily important 30 to 100 MHz range. The SSC Model Shop fabricated the Mark II vest antenna in accord with this design. For a small band of frequencies in the 30- to 100-MHz range, the matching was good. Unfortunately, this improvement was achieved at the expense of good matching in the higher frequencies. The gain and patterns of the Mark II were similar to the Mark I.

Far worse from the standpoint of a good antenna was the degradation of safety caused by leaking of the electromagnetic field into the Mark II vest. The electric field measured for the Mark II was higher than that of the Mark I with a purely horizontal gap. The idea that the metal vest would form a Faraday cage and protect the wearer was correct. Only within the gap did this assumption fail. The Mark II had a longer gap in which to admit high fields.

[1] The Mark I was a garment pulled over the head. The lower part was a 30-cm-wide band. The upper part covered the rest of the torso. A 2.5-cm gap separated the two parts.

[2] The VSWR for frequencies less than 100 MHz was greater than 5:1.

The Mark I was modified to permit very high values of input power. A jell was fabricated that simulated the dielectric and conductive properties of a person in the 150- to 500-MHz frequency range. Testing was done with the vest over a 34-liter container filled with jell. At frequencies of 250, 300, and 350 MHz with input power of 50 W applied for 30 minutes, the jell temperature increased by less than the 0.1° C of the resolution of the thermometer. This lack of temperature rise indicated that the Mark I vest antenna in the UHF band is probably safe from radiation hazard. The recipe for jell in the 3- to 150-MHz range involves the use of aluminum powder, a hazardous material. The tests at these frequencies were delayed until FY 2001.

Lebaric had one of his students fabricate an antenna shaped conformably to the standard Kevlar helmet. The material covered the entire helmet. The antenna had a straight gap. We designated this the Mark I helmet antenna. As an alternative, the SSC Model Shop fabricated a helmet antenna (designated the Mark II) with a saw-tooth gap. Although Mark II VSWR was better than Mark I, Mark I gain was much better. Differences were typically more than 10 dB. The Mark I gap was much narrower than the Mark II.

The three primary ideas derived from FY 1999 and FY 2000 work were that the gap should be a short as possible for radiation safety, the tests for impedance and matching must be done with the person wearing the vest, and the symmetry must be as high as possible. The differences in the gain between the Mark I and Mark II helmet antennas indicated that the gap must be horizontal and as narrow as possible.

The Mark III vest and helmet antennas incorporated these features. The physical aspects of the torso of the human body and of the helmet preclude imposing complete front-to-back symmetry. The symmetry of the Mark III vest antenna was broken to provide better matching in the important 30- to 100-MHz frequency range. An addition of "suspenders" provided a large signal path that allowed good matching in the very high frequency (VHF) range, which is important for tactical communications. In one measurement, the VSWR of the vest antenna was less than 3:1 for all frequencies between 35 and 475 MHz. In the more typical measurement, the VSWR would increase above 3:1 at approximately 300 MHz, but would level off at a maximum of 3.5:1.

For the helmet antenna, empirical studies showed that a second shorting strap placed at approximately the 2 o'clock position (the feed being at 6 o'clock and the first shorting strap at noon) would permit an excellent match over the whole 500- to 2000-MHz range. The VSWR of the helmet antenna was less than 3:1 for all frequencies between 440 and 2310 MHz.

Lebaric suggested that a prototype of the whole-body antenna could be efficient for frequencies between 2 and 30 MHz. Using FLECTRON, the material from which all the antennas have been made, conducting strips started at the feed region in the upper part of the back and went down the sides of the pants to terminate at the shoes. An insert of FLECTRON on the inner sole of the shoe coupled the antenna to the ground to complete the circuit. VSWR measurements when a 4:1 radio frequency (RF) transformer was inserted into the circuit showed the match was excellent. The VSWR was less than 2:1 for all frequencies between 5 and 30 MHz.

During FY 2001, experiments were conducted at SSC San Diego to measure the gain and patterns of the vest and helmet antennas. Both experiments were conducted with the antennas supported on Styrofoam because of the difficulty in making the measurements while wearing the antennas. The gain of the vest antenna in the 30- to 100-MHz range was a minimum of -10 dBi, comparable to the standard whip antenna. The gain increased to greater than 0 dBi in the 225- to 400-MHz range. The gain of the helmet antenna in the 400- to 2400-MHz range was between -5 and -15 dBi. The vertical polarization was almost always larger than horizontal.

Experiments were also conducted in FY 2001 to show the ability to use wideband radios. Two PRC-148 hand-held radios were loaned to SSC San Diego by the Marine Corps Systems Command for this purpose. The ability to transmit at a total of many pre-programmed frequencies in the VHF/UHF range, allows PRC-148 to stand in for the JTR that will be produced by FY 2007. Experiments showed that the transmission was completely dependent upon terrain. There is no place in the Point Loma region that has line-of-sight (LOS) distance of more than 3 km. All LOS radios fail at greater distances. This limitation was solved in FY 2002 by transmitting across San Diego Bay from Point Loma to Coronado. Transmission distances of more than 9 km for input power of 3 W were obtained. The Frequency Coordinator of Southern California allocated 10 frequencies between 60.9 and 450 MHz for these experiments. Extensive experiments were conducted at 6.2 km at all 10 frequencies. The power levels used successfully were as low as 0.1W at some frequencies. The connection was successful for all frequencies if the input power was larger than 1 W. When the wearer of the vest antenna was face down in the sand (again at a range of 6.2 km), there was two-way communication at frequencies of 63.9 and 142.425 MHz for several orientations and an input power of 5 W.

A site using the 802.11b protocol was set up to demonstrate the ability of the helmet antenna to receive video data. A camera focused upon the movement of the second hand of a clock. The signal from the camera transmitted the signal at a frequency of 2.4 GHz using a microstrip antenna. Another microstrip antenna inserted into a laptop computer received the signal and displayed it on the screen. The connection capable of transmitting data at a maximum rate of 11 Mb/s had options to transmit at lower data rates if the error became large. Thus, as the second microstrip antenna moved out of range of the first (a distance of 30 m), the decreasing data rate was demonstrated by the intermittent nature of the image on the laptop computer screen. Instead of showing an image moving at 1-s increments (similar to an old stopwatch), the image would display 5-s increments. At 60 m, the image stopped moving altogether. The output from the helmet antenna was inserted into a port in the microstrip antenna. The image moved at the 1-s increments as the wearer moved to the end of the SSC San Diego Model Range. The distance between the transmitter and receiver was 160 m.

Two-way communication for the helmet antenna was demonstrated at a distance of 6.2 km at a frequency of 1240 MHz.

Because of the power rating of the 4:1 RF transformer on the whole-body antenna, no attempt was made to transmit. An HF receiver was connected to the output of the whole-body antenna worn by a person. Station WWV in Boulder, CO, transmits a beep every second and the time in Greenwich, England, every minute at frequencies of 5, 10, 15, and 20 MHz. This signal was broadcast audibly and clearly by the receiver attached to the whole-body antenna. The signal level was approximately half that of a 35-foot whip.

The experiments on radiation safety during FY 2000 have been described. Many experiments to measure the electric field were conducted on the empty vest antenna during FY 2001 and FY 2002. A bi-directional coupler that permitted measurements of the forward and reflected power was inserted at the output of a 50-dB amplifier transmitting a power of 5 W. Measurement of the reflected power and the application of the square-root scaling of the electric field as a function of the net power allowed translation of the results from the empty vest to those of one on a person. The measurements indicated that the field at a height parallel to the feed was a factor of 3 too large for safety at frequencies near 50 MHz. Experiments conducted with an implantable electric field probe in a jell man indicated a severe problem.

Workers at the Naval Health Research Center (NHRC) at Brooks Air Force Base (AFB) in San Antonio, TX, conducted experiments on radiation hazards during FY 2001 and FY 2002. Dr. John D'Andrea of the NHRC is one of the country's experts on establishing and measuring radiation hazards. Using temperature sensors to measure the specific absorption rate, NHRC determined that the Mark III vest antenna allowed too much field into the vest for safety at an input power of 5 W. When the vest was modified to absorb and reflect the energy that leaked into the gap of the vest, experiments showed that the vest met the safety standards for all frequencies between 30 and 90 MHz, even for input power as high as 25 W. Since 5 W is the maximum input power expected for the hand-held JTR, the modified vest antenna should be safe to use at all frequencies. Measurements conducted on the empty vest indicated that the fields inside were lower than the maximum permitted for all frequencies higher than 120 MHz.

The U.S. Army conducted experiments on the unmodified Mark III vest at Fort Huachuca, AZ, in June 2001. The experiments confirmed that there was a radiation safety hazard for input power as high as 5 W. Most importantly the experiments showed that the gain of the vest antenna was significantly reduced (as much as 20 dB in the 225- to 400-MHz range) when worn by a person compared to that on a Styrofoam model. These results were confirmed during experiments on gain conducted in June 2002 at SSC San Diego. Work must be done on improving the gain of the vest antenna, especially in the UHF range.

During FY 2001, workers at SSC San Diego developed a distribution system for signals to the three antennas. Using a simple single-pole, three-throw switch powered by a battery-powered rotary switch on the wrist of the wearer, the distribution system successfully routed the signals from the output of the radio to the appropriate antenna. At all frequencies between 5 and 1200 MHz (the limit of the network analyzer used), system VSWR was less than 3:1. For the frequencies higher than 1200 MHz, the helmet antenna gave a good match.

During FY 2002, work was done to make the vest antenna sufficiently rugged for military use. A method was found to make the copper waterproof (Kiwi spray for tents). A backing of urethane was impervious to water. Snaps and a silicon jell that solidified into a hard substance made the feed very rugged.

CONTENTS

Figures

Tables

INTRODUCTION

The goal of the **COM**bat **W**ear **In**tegration (COMWIN) antenna project is to develop a soldier-carried antenna that meets two aims. The first is to transmit or receive a signal at any frequency between 2 MHz and 2 GHz. This aim is based upon the Operational Requirements Document (ORD) of the Joint Tactical Radio System (JTRS) (ORD for JTR, 1998). The second is to hide the identity of the radio operator, at least visually. This aim is based upon reports from the Vietnam War and the Russian misadventure in Chechnya that snipers preferentially target radio operators and the officers nearby [Reference Thomas, 1999]. The snipers seek to disrupt the command, communications, and control functions at the squad level. Making the radio operator indistinguishable from other soldiers would help protect the squad from disruption. The snipers can often easily identify the radio operator by the large whip antenna attached to a box on the soldier's back.

Integration of the antenna into the uniform of the soldier can help meet both aims. Integration of the antenna into the uniform hides the identity of the radio operator. The radio operator would be indistinguishable from any other soldier. The integration also provides the maximum amount of surface area for a given length. Increasing the surface area, if done cleverly, can increase antenna bandwidth by increasing the number of paths a signal can use to radiate energy.

RESULTS FROM PREVIOUS YEARS

The origins of the COMWIN project stem from the realization that the hand-held JTR had no antenna suitable for the full 2-MHz to 2-GHz frequency range. Maj. Jim Devers of the Marine Corps Systems Command (MARCORSYSCOM) and Lt. (now LCDR) Howard Pace of the U.S. Navy (USN) detailed to SSC San Diego developed a project to correct this deficiency. MARCORSYSCOM provided initial funding. They chose Dr. Jovan Lebaric, a Professor of Electrical Engineering at the Naval Postgraduate School (NPS) in Monterey, CA, to provide technical leadership. They also chose LCDR Peter Haglind of the Swedish Navy, detailed to SSC San Diego for a year as project head, and Dr. Richard Adams of SSC San Diego as a technical consultant. Lebaric provided innovative designs and calculations. The NPS also provided student assistance in theoretical work and fabrication. Maj. T. M. Gainor of the U.S. Marine Corps did the initial calculations for the vest antenna. Ah Tuan Tan from the Singapore Ministry of Defense did the calculations for the helmet antenna and fabricated the Mark I version of this device. Maj. Todd Emo performed calculations on the whole-body antenna. Lt. Brown (USN) did radio tests with a version of the vest antenna.

Maj. Devers described the antenna goals of the project. The first goal was that the voltage standing wave ratio (VSWR) had to be less than 3:1 over the frequency range. The second goal was that the polarization of the antenna was to be vertical if the person was standing. There were to be no major nulls in the elevation pattern up to an angle of 60°. Finally, the antenna had to be safe to use. The radiation hazard had to be less than that prescribed as safe by the Institute of Electronics and Electrical Engineers (IEEE), the Department of Defense, and the Department of the Navy. Fortunately, in the frequency range between 30 and 2000 MHz, all the standards agree (IEEE C95.1-1991, DODI 6055.11, 1995, and OPNAVINST 5100.23E, 1997).

FY 1999

The COMWIN project started at SSC San Diego and NPS in May 1999. Literature research was conducted and preliminary models were developed using the software GNEC under the leadership of Professor Jovan Lebaric and Professor Richard Adler of NPS. The GNEC program uses Method of Moments to predict the impedance and the radiation patterns. Professor Lebaric and his colleagues decided that no one antenna could possibly cover the 2-MHz to 2-GHz frequency range. Lebaric suggested three antennas. An antenna in the form of a vest would cover the 30- to 500-MHz range. One in the form of a helmet would cover the 500- to 2000-MHz range. Finally, one that would use the whole body could cover the high-frequency (HF) range of 2 to 30 MHz. Lebaric's original concept has driven project development. He also suggested the acronym, COMWIN.

Lebaric proposed a brilliant way to increase antenna bandwidth. In the vest antenna, a gap (width approximately 1 inch) separates the device into an upper and lower part. The feed is at the rear of the vest. The vest acts much like a fat dipole. The impedance becomes largely capacitive at the higher frequencies. Lebaric's models put a shorting strap at the front of the vest. This addition provided inductance that largely cancelled the capacitance so that the impedance became resistive. Another way to look at this addition was to think of the vest as the combination of dipole and loop. These antennas have maximums and minimums of the VSWR that vary periodically with frequency. The minimums of the VSWR for the dipole and loop alternate. Combining the two antennas provides an impedance that varies much less than using either of the two antennas separately. A prototype of the vest antenna was fabricated at the SSC San Diego Model Shop in August 1999 and tested on the Model Range.

There was a rush to develop a prototype from a technical and publicity standpoint. Lebaric's theoretical predictions for impedance and patterns needed validation. Some practical results were also needed.

Figures 1 and 2 show the initial model (Mark I) of the COMWIN vest antenna. Figure 1 shows a view from the front. In that photograph, LCDR Peter Haglind of the Swedish Navy is wearing the vest. He was the original head of the project. Unfortunately, he returned to Sweden in December 1999. The shorting strap is evident in the photograph as a piece of copper tape in the middle of the vest. Figure 2 shows a rear view of the Mark I vest antenna.

Figure 1. Front of Mark I COMWIN vest antenna. LCDR Peter Haglind of Swedish Navy, shown wearing the vest, was the first head of project from May to December 1999.

Work in FY 1999 identified a material, FLECTRON, made by Advanced Precision Materials (APM) of St. Louis, MO. Originally part of Monsanto, APM is now part of Laird Technologies. For all subsequent work, FLECTRON has been used as the material for the COMWIN antennas. Copper tape was used in regions with soldering. The low melting point of FLECTRON (210° C) requires special solder that is not readily available. Table 1 shows a summary of the characteristics of FLECTRON. FLECTRON is a non-woven mixture of copper and polyester. The material is lightweight and highly conductive. The material even permits air to pass through. In 1999, the cost was $18/square/yard. The latest price is approximately twice that.

Figure 2. Rear of Mark I COMWIN vest antenna placed on a Styrofoam mannequin. Copper tape was used where soldering was done due to low melting point of FLECTRON. Professor Adler of the NPS suggested a zigzag pattern for the copper tape to increase coupling to FLECTRON. This pattern has not been continued in the latest versions.

Table 1. FLECTRON properties (Product No. 3027-106 from APM)

Property	Value	Units
Basis weight	51 to 78	g/m^2
Metal weight	10 to 24	g/m^2
Thickness	0.487	mm
Surface resistivity	<0.1	Ohms/square
Shielding effectiveness	80	dB at 100 MHz
Tensile strength	131/324	N/100 mm
Maximum short duration temperature	210	°C

In more conventional units, a 0.1-ohms/square resistivity implies that the conductivity of the material is greater than 20.5×10^3 S/m. By contrast, copper has a conductivity of 6×10^7 S/m.

Lebaric predicted that the vest antenna would have a resonance at a frequency of 90 MHz. This resonance is largely due to the dimensions of the vest. The finite conductivity of the material reduces the peak impedance but does not change the character of the resonance.

Figure 3 shows a comparison of the predicted impedance with that measured for the vest antenna on a Styrofoam mannequin at the SSC San Diego Model Range in August 1999. The results confirmed the predictions qualitatively and quantitatively. The measured impedance was usually within 10% of the predicted impedance. The assumption of perfect conductivity in the calculation led to a factor of 2 error in the impedance at the resonance point.

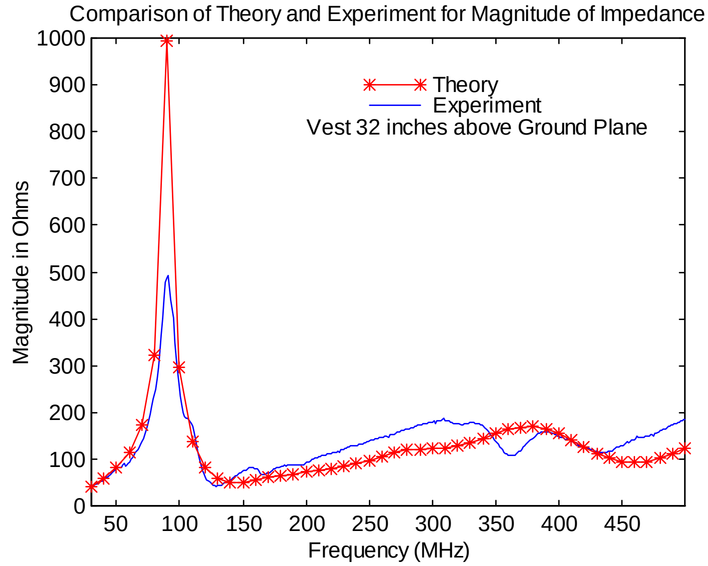


Figure 3. Comparison of theoretical prediction using GNEC of absolute value of impedance of the Mark I vest antenna. Discrepancy is less than 10% except for frequencies near resonance.

Figure 4 shows the impedance of the Mark I vest antenna with and without a person wearing it. The introduction of the impedance of the wearer changed the frequency of the resonance and reduced its magnitude significantly. The impedance varies much less than with an empty vest.

A second feature of the theoretical results was that the impedance of the empty vest was relatively constant in the frequency range between 100 and 500 MHz. The average value was 125 ohms. This observation led to the insertion of a 2:1 transformer into the circuit. The transformer had the restriction of a maximum power input of 0.25 W (Mini-Circuits 1997). This restriction implied that the vest with this impedance matching device could not be used for transmission of high power or for radiation hazard studies. Figure 5 shows the effect of the introduction of the transformer on VSWR. VSWR was less than 3:1 for almost all frequencies between 100 and 500 MHz.

Lebaric made predictions of the patterns generated by the vest antenna. Measurements made at the Model Range in late September 1999 allowed a comparison between theory and experiment. The theoretical and experimental azimuth patterns were very similar. The use of an arbitrary scale factor that was the value of the radiated power at 0° azimuth allowed this comparison. Unfortunately, no predictions of gain could be made from GNEC.A great deal of work was necessary to obtain a good comparison between theory and experiment for the elevation pattern. Details on the conductivity of the lead paint on the Model Range were important for obtaining a good comparison.

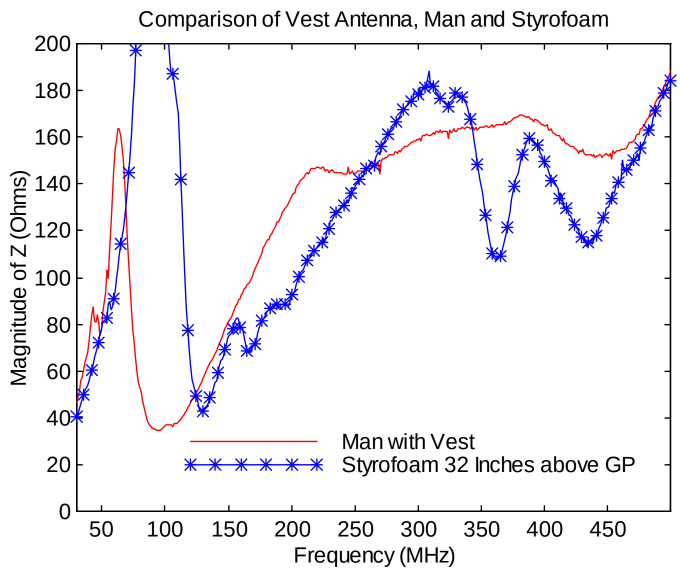


Figure 4. Effect of wearer upon impedance of Mark I vest antenna. Resonance changes frequency and variation is markedly reduced.

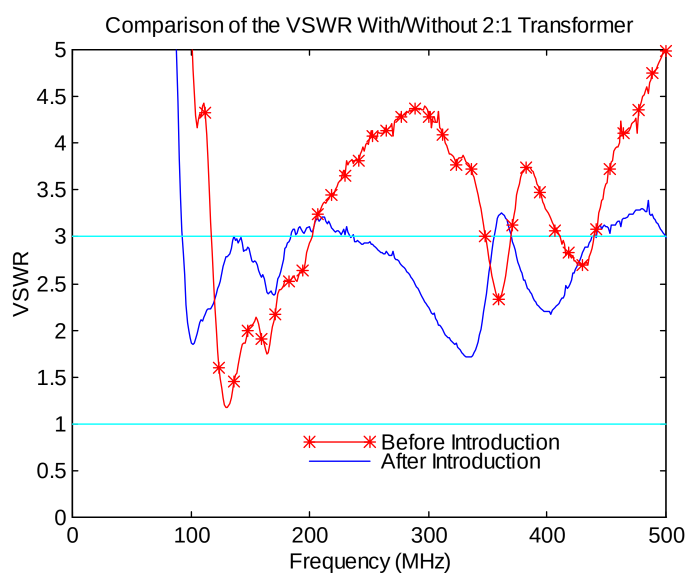
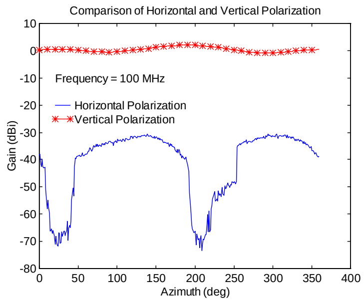
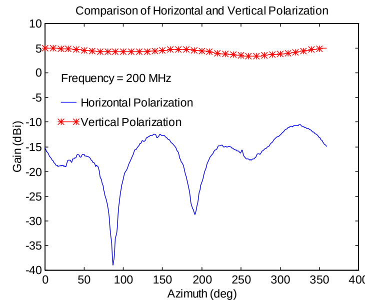


Figure 5. VSWR of Mark I vest antenna on Styrofoam mannequin before and after introduction of 2:1 transformer. Because impedance was relatively constant with an average of 125 ohms, VSWR was less than 3:1 for most frequencies between 100 and 500 MHz.

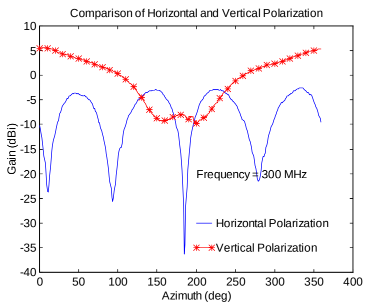
Figure 6 shows the radiation pattern of the vest antenna on the Styrofoam mannequin for vertical and horizontal polarizations for frequencies between 100 and 500 MHz in 100-MHz steps.



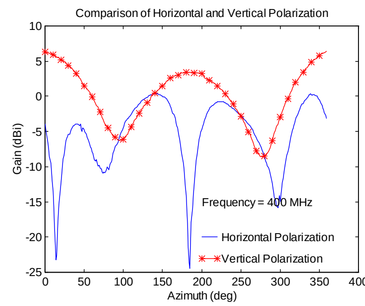
6a. Frequency = 100 MHz



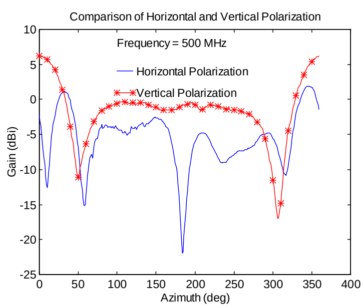
6b. Frequency = 200 MHz



6c. Frequency = 300 MHz



6d. Frequency = 400 MHz



6e. Frequency = 500 MHz

Figure 6. Radiation Patterns at 3° elevation at five frequencies. Gain relative to an isotropic source are diplayed. All values of power received were normalized by comparing signals to calibrated, quarter-wave monopole whose gain was 5.15 dBi.

The gain of the vest antenna varies from a minimum of 2 dBi at 100 MHz to a maximum of 6 dBi at 500 MHz. The radiation patterns show one disturbing trend that has occurred in all of the subsequent COMWIN antennas. The antenna becomes electrically large in the frequency region higher than about 250 MHz. This large electrical size is manifest by the large nulls and numerous lobes as the frequency increases. Without highly complex electronics this is one characteristic that will probably remain due to the length scales involved (Adams et al., 1999).

Many of these results were presented at the MILCOM 2000 conference held in Los Angeles (Abramo et al., 2000).

FY 2000

Since the JTRS ORD calls for an antenna system that works from 2 MHz to 2 GHz, work began to enlarge the bandwidth of the vest antenna and to fabricate a helmet antenna. There was also the need to measure, assess, and, if necessary, mitigate radiation hazards. Both efforts started during FY 2000. CW05 Francisco Canez was the project head from January to May 2000. He left to act as liason for the production of the Digital Modular Radio at Motorola in Phoenix, AZ. LCDR Wrightson assumed the role of project head from May to July 2000. Richard Adams became project head in July 2000. The association between COMWIN and Professor Lebarie ended in September 2000.

Vest Antenna

Lebaric suggested a method to obtain a low VSWR by enlarging the length over which the wave must pass as it is radiated. If the gap were in the form of a saw tooth (somewhat like Charlie Brown's sweater), the electrical length and efficiency in the 30- to 100-MHz frequency range should increase. Lebaric had done much modeling using GNEC to predict the effect of the saw-tooth pattern on impedance. The results were consistent with his intuition.

A new vest antenna (designated the Mark II) was fabricated at the SSC San Diego Model Shop by Bob O'Neill. Figures 7 and 8 show the front and rear views, respectively, along with the Mark II helmet antenna described below. Because of the asymmetry of the vest, the saw-tooth pattern could not be perfectly regular. The width of the gap could not be held uniform.

Figure 7a. Front view of Mark II COMWIN vest antenna with Mark II helmet antenna. Mark II is different from Mark I in having a saw-tooth pattern in the gap and slightly less material near the shoulders.

Figure 7b. Rear view of Mark II COMWIN vest antenna. A 2:1 transformer was inserted into circuit to aid in matching of antenna.

Figure 8 shows a plot of the VSWR of the Mark II vest antenna with the transformer inserted in the circuit. The impedance was measured with and without a flak jacket between the antenna and the person. Although the overall VSWR was improved by making the gap a saw-tooth pattern, at some frequencies, the VSWR worsened. The improvement occurred in the frequency range between 50 and 60 MHz. Since the 30- to 88-MHz frequency range is critical for the U.S. Marines, this improvement is essential. Unfortunately, the lengthening of the gap also led to increased radiation leaking into the interior of the vest and to a significant radiation hazard. This assessment will be described in the section on radiation hazard

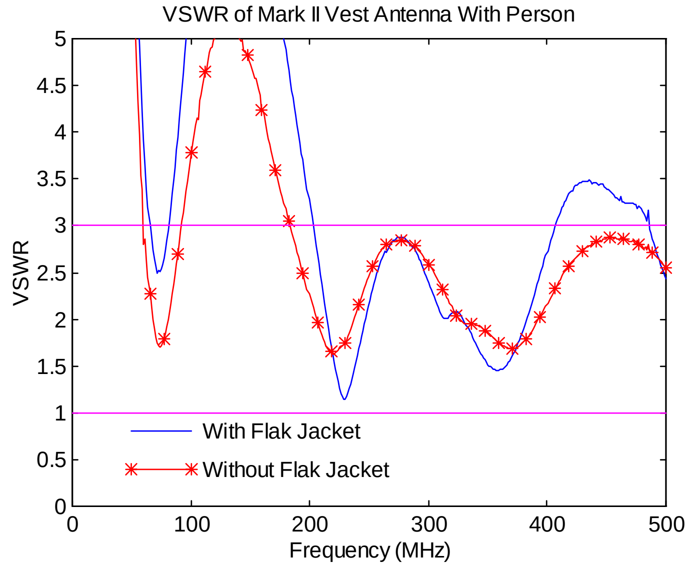


Figure 8. VSWR versus frequency of Mark II vest antenna on person with and without a flak jacket between antenna and person. A 2:1 transformer was inserted into circuit.

Many measurements of the gain and radiation patterns were made on the SSC San Diego Antenna Range. Gain was measured by comparing the signal from the test antenna with a calibrated log-periodic one. The SSC San Diego antenna range has many desirable features, including a canyon between the transmitting and receiving antenna. The walls of the canyon minimize the inaccuracies caused by ground reflection. There is no reflecting surface to the rear of the receiving antenna, only the Pacific Ocean 200 feet below.

Figure 9 shows the gain at boresight of the Mark II vest antenna in vertical polarization. Boresight is the orientation in which the front of the vest antenna faces directly at the transmitter. A Styrofoam model supported the antenna. Figure 10 shows the difference between boresight gain in vertical polarization to that in horizontal polarization. At frequencies less than 100 MHz, a significant portion of the signal is radiated in horizontal polarization. The ratio of vertical to horizontal signal increases as the frequency increases.

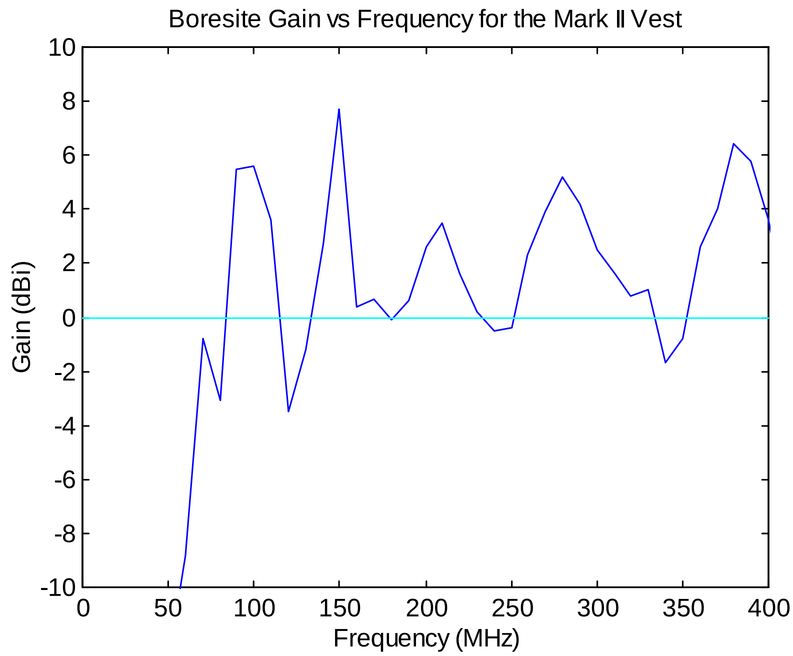


Figure 9. Boresight gain of Mark II vest antenna versus frequency between 50 and 400 MHz. A Styrofoam model supported antenna. Transmitter was vertically polarized.

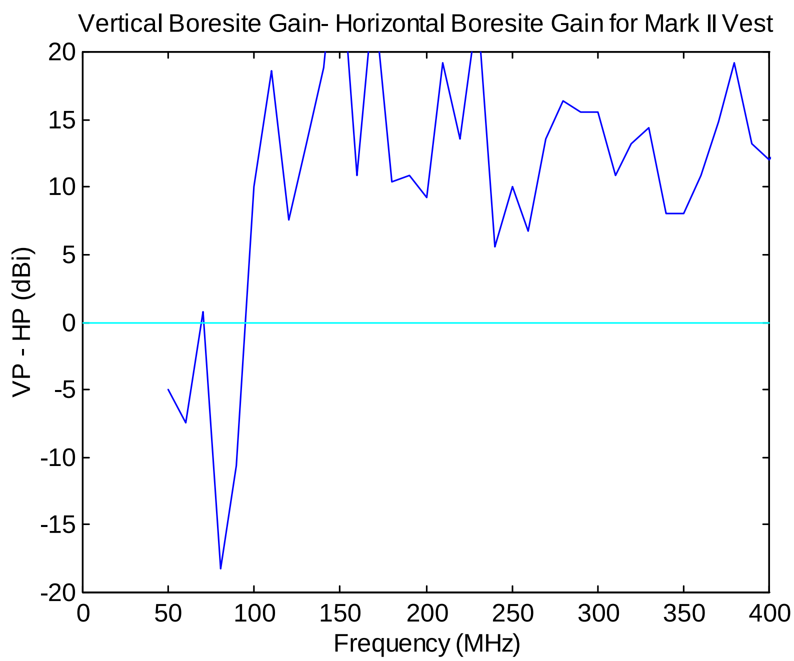


Figure 10. Difference in boresight gain between vertical and horizontal polarizations of Mark II vest antenna versus frequency.

Helmet Antenna

For FY 2000, Lebaric designed a helmet antenna (fabricated and tested by his student, Ah Tuan Tan) that had many of the same features as the vest (gap parallel to the ground and shorting strap on the side opposite to the feed). Lebaric gave this helmet antenna to SSC San Diego for further testing. As an alternative to the helmet antenna fabricated at NPS, SSC San Diego fabricated one that had a saw-tooth pattern (Adams et al., 2000). We designated the NPS helmet antenna as the Mark I and SSC San Diego helmet antenna as the Mark II.

Figures 11a and 11b show a front and side view, respectively, of the Mark I helmet antenna. Figures 7a and 7b show the corresponding photographs for the Mark II helmet antenna. The gap on the Mark I, besides being horizontal, is also much narrower than the Mark II. Both antennas have fabric covering the entire top of the helmet.

Front view

Side view

Figure 11. Mark I helmet antenna fabricated by Ah Tuan Tan of NPS.

The VSWR was measured using a Hewlett Packard® 8510 network analyzer at the San Diego Model Range. The ground plane was far enough away so that it probably did not affect the measurements. Figure 12 shows a comparison of the VSWR of the Mark I and Mark II helmet antennas. The Mark II has a much better VSWR than the Mark I. For 247 frequencies out of 401 between 300 and 2000 MHz, the VSWR of the Mark II was less than 3. The comparable total for the Mark I was only 120.

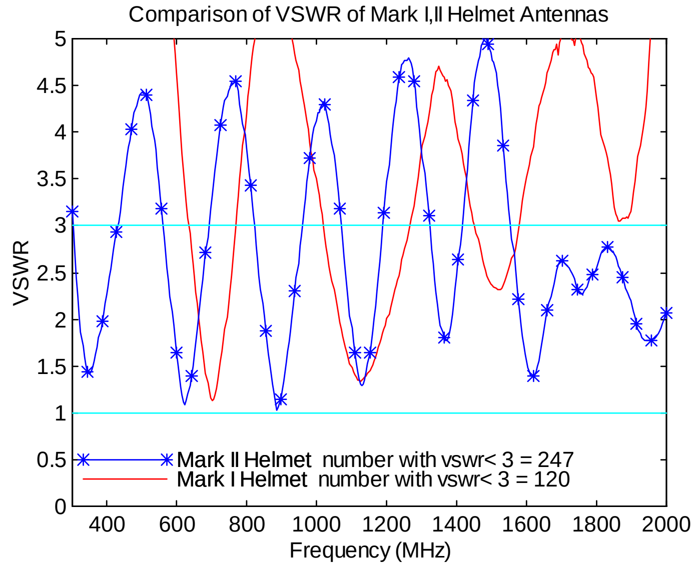


Figure 12. VSWR versus frequency for Mark I and Mark II helmet antennas. VSWR of Mark II is usually better than Mark I.

Measurements of boresight gain and radiation patterns for the Mark I and Mark II helmet antennas were made in the anechoic chamber at SSC San Diego. The log-periodic antenna for the vest antenna was used as the reference for determining gain. Only boresight gain in the vertical direction was measured. Figure 13 shows a comparison of the boresight gain for the Mark I and Mark II helmet antennas. Although the Mark II VSWR is consistently better, the gain of the Mark I is higher. Gain is a better parameter for determining antenna effectiveness than VSWR. A Kevlar helmet supported the antennas in the anechoic chamber.

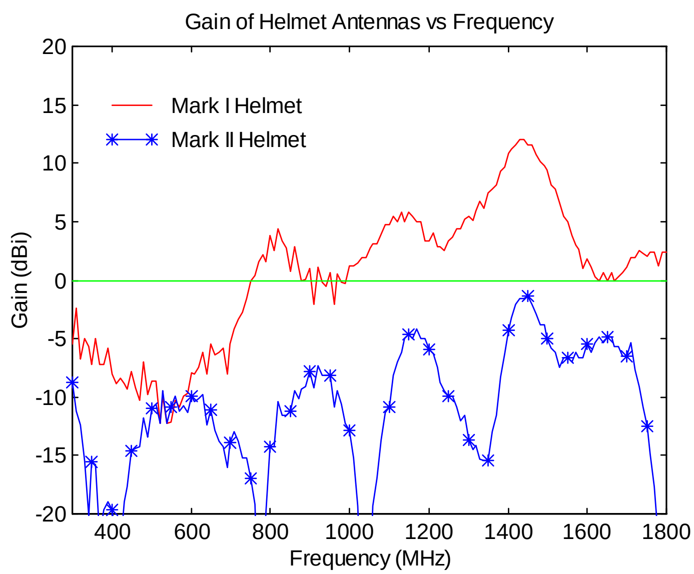


Figure 13. Boresight gain in vertical direction for Mark I and Mark II helmet antennas.

Vest Antenna Radiation Hazard Studies

Radiation hazard studies started. The matching circuit from the Mark I vest antenna was changed to accommodate more power (the RF transformer used for matching had a maximum power rating of 0.25 W). Studies were also conducted to demonstrate that the electric field within the vest was proportional to the square root of the input power. Such a demonstration of scaling was important because the RF transformer on the Mark II vest antenna limited power. Extrapolation from low-power measurements would be one method to demonstrate the safety of the antenna from radiation hazards.

Figures 14a and 14b demonstrate the scaling of the measured electric power inside the Mark II vest antenna. The input power was channeled directly from a signal generator. The nominal power was 2 to 20 dBm. Return power was not measured. Figure 14a shows the scaling for one frequency and many values of input power. Figure 14b shows the scaling of the electric field for many frequencies and two values of input power.

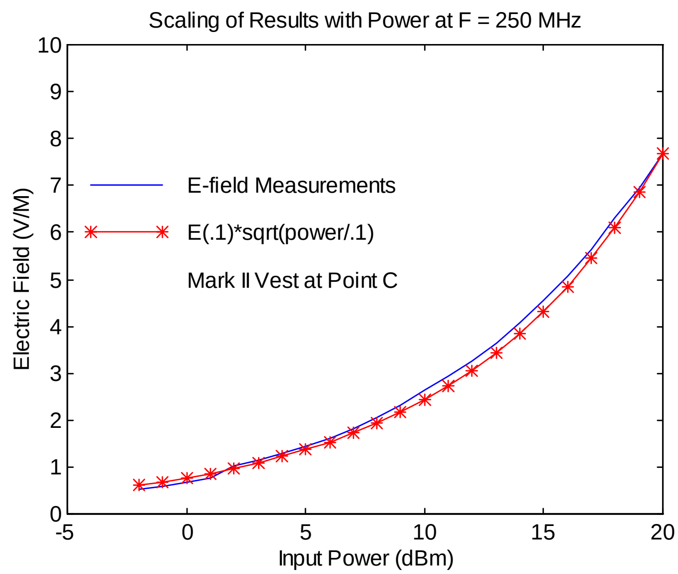


Figure 14a. Measured electric field at one frequency and many values of input power. Value of electric field for input power of 20 dBm normalized results.

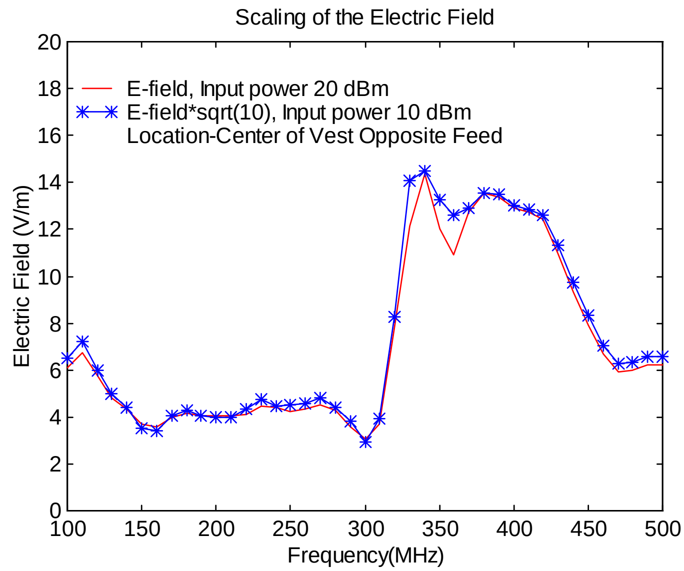


Figure 14b. Measured electric field for two values of input power. Electric field for value was multiplied by square root of 10, ratio of input powers.

The measurements of the electric field were made with an EMCO™ electric field sensor. This device has excellent sensitivity (0.5 V/m) for all frequencies between 10 and 1000 MHz. The probe processes the results from three orthogonal dipoles to produce a result independent of orientation. Such devices are isotropic.

Measurements of the electric field within the FY 1999 and FY 2000 vest antennas indicatedthat the saw-tooth pattern of the gap for the Mark II allowed more field to leak into the body than a straight gap. The extrapolated fields were almost always less for the straight-gap Mark I vest antenna. For frequencies around 90 MHz (the frequency modulation [FM] broadcast band), the electric fields within both models of vest near the feed were higher than those allowed by the IEEE standards for whole-body exposure. These fields almost always decreased with increasing distance from the feed. For the saw-tooth pattern vest antenna, the electric field near the feed at frequencies around 300 MHz was larger than that prescribed by the standard.

Figures 15a and 15b present the values of electric field for the Mark I and Mark II. The fields have been extrapolated from the measurements to an input power of 5 W. The fields of the Mark I vest are consistently lower than those of the Mark II. The saw-tooth gap design lengthens the gap, allowing excessive field into the interior.

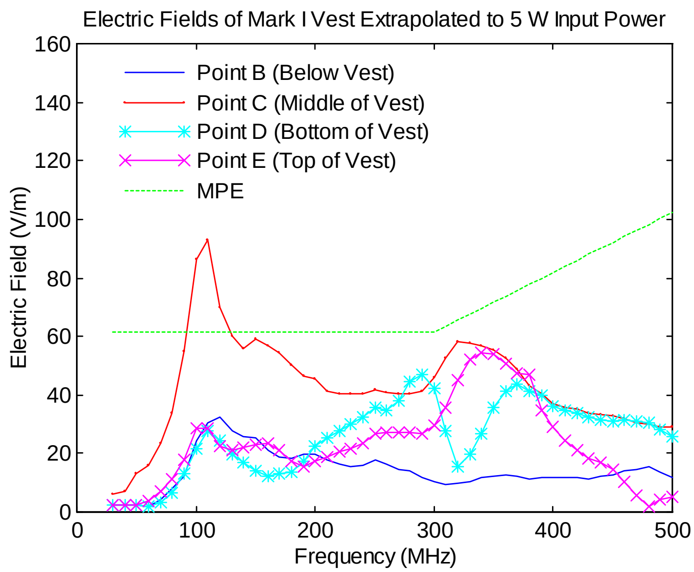


Figure 15a. Electric fields of Mark I vest antenna extrapolated to input power of 5 W. Fields were measured at various places as a function of frequency and results scaled to 5 W.

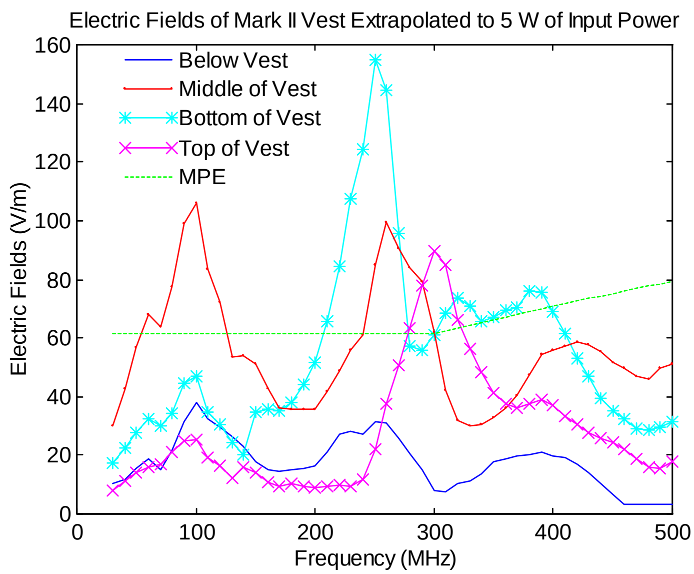


Figure 15b. Electric fields of Mark II vest antenna extrapolated to input power of 5 W. Fields were measured at various places as a function of frequency and results scaled to 5 W.

The modification of the matching circuit of the Mark I vest antenna allowed high levels of input power. The Mark I was used for studies of heating within the body. A plastic container of 34 kg of salt water was used as a test. The VSWR of the vest antenna was excellent at frequencies between 250 and 350 MHz. After the input of 50 W of power for 30 minutes, the measured temperature at the end of the experiment was no higher within the 0.1° C resolution of the thermometer than at the beginning (Adams et al., 2000).

A jell that simulated the dielectric and conductive properties of a person in the 100- to 500-MHz frequency range was mixed. Chou et al. (1984) provide the recipe for the mixture. Measurements of the impedance of the vest on a person or a 34-kg container filled with jell showed the mixture was similar to a human being. Experiments on measuring the temperature after the input of 50 W of power for 30 minutes showed no heating by the vest antenna. The experiments were repeated five times with similar results. The frequencies used were 250, 300, and 350 MHz (Adams et al., 2000).

FY 2001

The conclusion of the FY 2000 work was that the gap should be horizontal. Professor Lebaric suggested that we impose maximum symmetry upon the design. At a minimum, there should be symmetry from top to bottom and from right to left. The asymmetry of the human body prevents symmetry from front to back. We could break symmetry in a consistent way to achieve a particular goal, e.g. the minimization of the VSWR. For the vest antenna, the breaking of symmetry would be the use of “suspenders” to improve the VSWR in the 30- to 100-MHz range. For the helmet antenna, a second shorting strap, empirically determined from VSWR, would break symmetry. Less FLECTRON would be needed because the vest only came up to the armpits. To satisfy this symmetry, the top of the helmet antenna had to be open.

A second feature became apparent through the FY 2000 work. The antenna had to be matched with the person wearing it. The presence of the person had such a profound influence on the impedance that any attempt to do the matching without the person made no sense. This influence might also mean that such features as gain must be measured only while a person was wearing the antenna, which became much more apparent during the FY 2002.

Vest Antenna

Figure 16 shows the front view of the Mark III vest antenna. The maximum allowable right-to-left symmetry was imposed. There is a great deal of symmetry from top to bottom (the top part of the antenna has the same dimensions as the bottom). The symmetry is broken by the addition of suspenders used for improving the matching of the antenna in the frequency range 30 to 100 MHz. Figure 17 shows a close-up view of the feed region of the Mark III antenna. The measurement of the impedance without any matching circuit indicated that the addition of a capacitor would permit very good matching. Another change was the addition of snaps to aid in taking the vest antenna off the body. Both the Mark I and Mark II vest antennas pulled over the head.

Figure 16. Front view of Mark III vest antenna. Maximum symmetry (right to left and top to bottom) was imposed on design. Symmetry was broken by suspenders to aid in matching in 30- to 100-MHz frequency range.

Figure 17. Close-up view of feed region of Mark III vest antenna. Capacitor with size 56 pf allowed good matching for 30- to 500-MHz frequency range.

In one version of the Mark III vest antenna, a single-pole, two-throw switch was added to aid in matching. Switching diverted the signal to a 68-pf capacitor for better matching in the 30- to 100-MHz range or to a 24-pf capacitor for 100- to 500-MHz range. Later, when designing the distribution system, it was found that this switch provided a back path. The back path complicated the distribution system. During August 2001, a single capacitor with size 56 pf provided an excellent match over the entire 30- to 500-MHz range.

Figure 18 shows the VSWR of the Mark III vest antenna. The addition of a flak jacket over the antenna has almost no effect upon antenna VSWR. Figure 19 shows one meaning of ultra broadband. The VSWR of the vest antenna is compared to two antennas manufactured by ICOM for its multi-band radio. The ICOM antenna provides excellent response for four bands (approximately 50, 145, 440, and 1240 MHz). The VSWR is large at virtually every other frequency. The antenna is unusable at these other frequencies. The antenna is excellent for the amateur band frequencies for which the radio can be used legally.

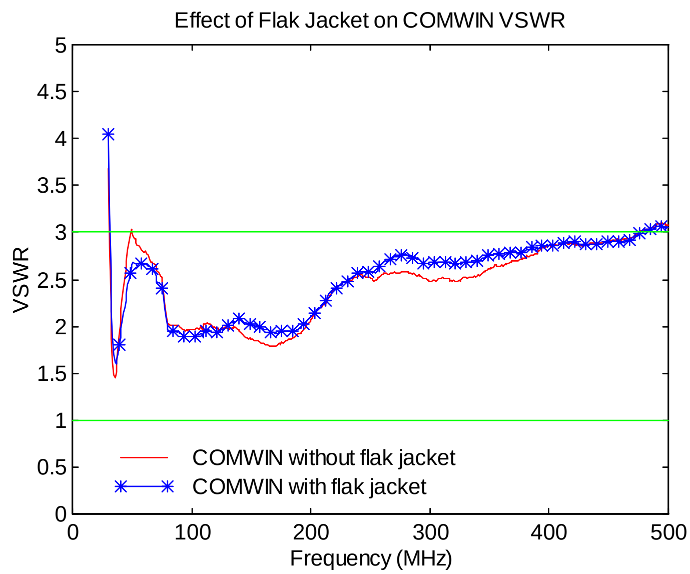


Figure 18. VSWR versus frequency of Mark III vest antenna with and without flak jacket. Flak jacket worn over antenna has almost no effect upon VSWR.

The VSWR displayed in Figure 18 for the vest antenna is the best ever obtained. In the more typical determination, the VSWR rises above 3:1 at 300 MHz and levels off at 3.5:1 at 400 MHz. The VSWR in Figure 18 was obtained shortly after the vest antenna was removed from a suitcase.

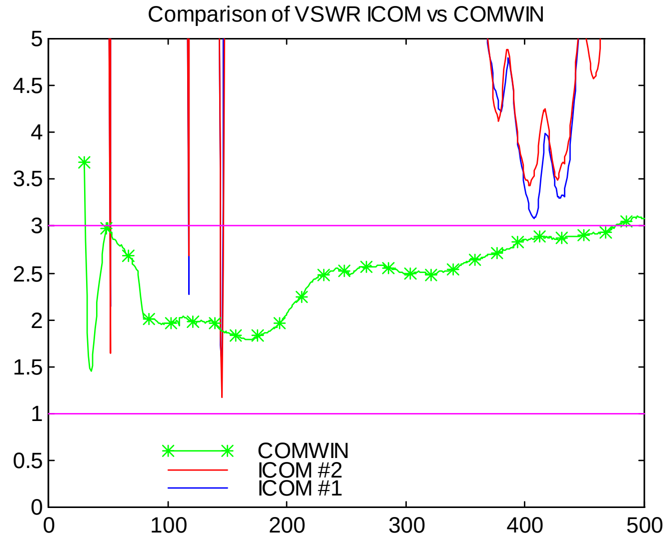


Figure 19. VSWR versus frequency of Mark III vest antenna compared with "rubber duck" antennas used for ICOM amateur band radios. ICOM antennas are excellent for four amateur bands, but unusable at other frequencies. COMWIN antenna VSWR is good at almost all frequencies between 30 and 500 MHz.

Figure 20 shows the gain in the vertical and horizontal directions of polarization for the Mark III vest antenna. The gain in the vertical almost always dominates. The gain in the horizontal polarization is important if the radio operator is to communicate in the prone position. This figure for gain is probably misleading since a Styrofoam model was used to support the antenna. The gain of the vest antenna with a person wearing it is much less for frequencies higher than 100 MHz.

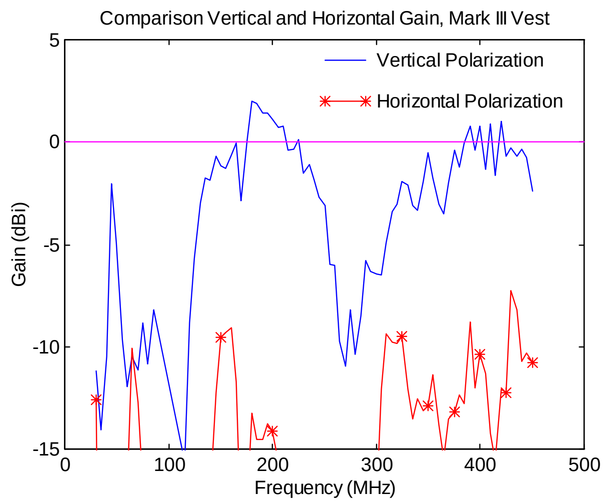


Figure 20. Gain in the vertical and horizontal directions for Mark III vest antenna as a function of frequency. A Styrofoam model supported the vest antenna. By comparison, gain of whip antenna for PRC-148 hand-held radio was advertised as -10 dBi.

Experiments were also done to measure the gain of the Mark III vest antenna when worn by a person. One of us (RCA) wore the antenna and stood facing the transmitter. Another (DWV) varied the frequency of transmission and recorded the power levels output from the amplifier. The last member (RSA) recorded the signal levels from a spectrum analyzer. A VHF radio provided by SSC San Diego permitted coordination of the transmit and receive functions.

Figure 21 presents the boresight gain versus frequency of the Mark III vest antenna for vertical polarization when worn by a person. Figure 22 shows similar data for horizontal polarization. The transmit antenna (a vehicular-mounted SINCGARS whip) did not work well enough when lying on the ground to record horizontally polarized signals.

These figures display a very disturbing feature. Although the soldier-worn vest antenna shows reasonably good gain on the 30- to 90-MHz frequency range, there is a significant decrease in gain in the 100- to 500-MHz range. This decrease is difficult to explain, considering the success the vest had using the PRC-148 radios across San Diego Bay. These results will be described below.

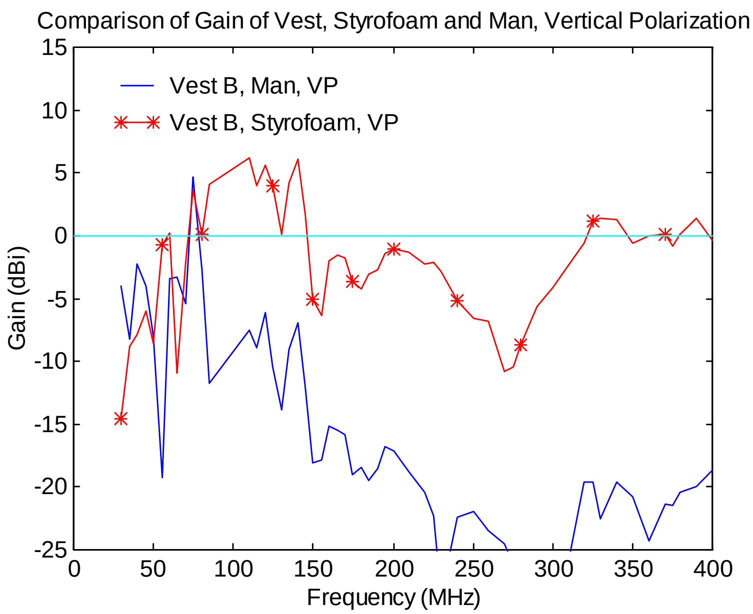


Figure 21. Boresight gain of Mark III vest on Styrofoam model and on man versus frequency. The transmitter had vertical polarization.

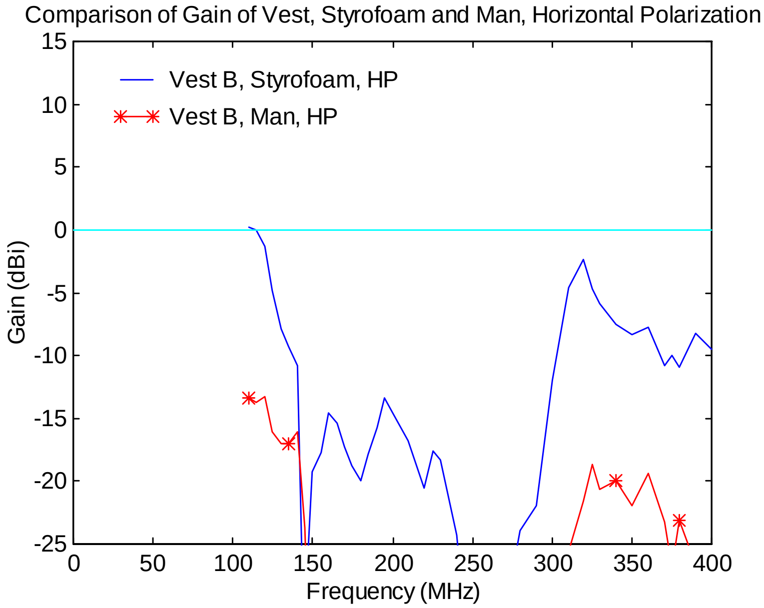


Figure 22. Boresight gain of Mark III vest on Styrofoam model and on man versus frequency. Transmitter had horizontal polarization.

Figure 23 shows the radiation pattern normalized to boresight (phi = 0°) for 11 frequencies between 50 and 400 MHz. The frequency of 170 MHz was used due to the high noise at 175 MHz at the outdoor SSC San Diego Antenna Range across the bay from the city. The nulls near the arms are prominent features in the patterns for frequencies near 400 MHz.

Figure 24 shows the elevation patterns for a boresight azimuth pattern for the same 11 frequencies. For many higher frequencies, the maximum in the elevation pattern does not occur at the horizon. This feature is desirable for an antenna that communicates with helicopters and aircraft.

During the latter part of FY 2001, the PRC-148 radios were used to conduct radio tests on the vest antenna. There was success for the legacy and COMWIN antennas as long as there was no obstruction between transmitter and receiver. Many attempts were made to find spots within Point Loma that had a large line-of-sight (LOS) distance. The uneven terrain limited LOS distances to no more than 3 km. All LOS antennas, including those provided for the PRC-148 radios, failed at these larger distances within Point Loma. During FY 2002, permission was granted from the Communications Security (COMSEC) Material System (CMS) custodian to take the radios off the base. Transmission across San Diego Bay provided the longer unobstructed distances.

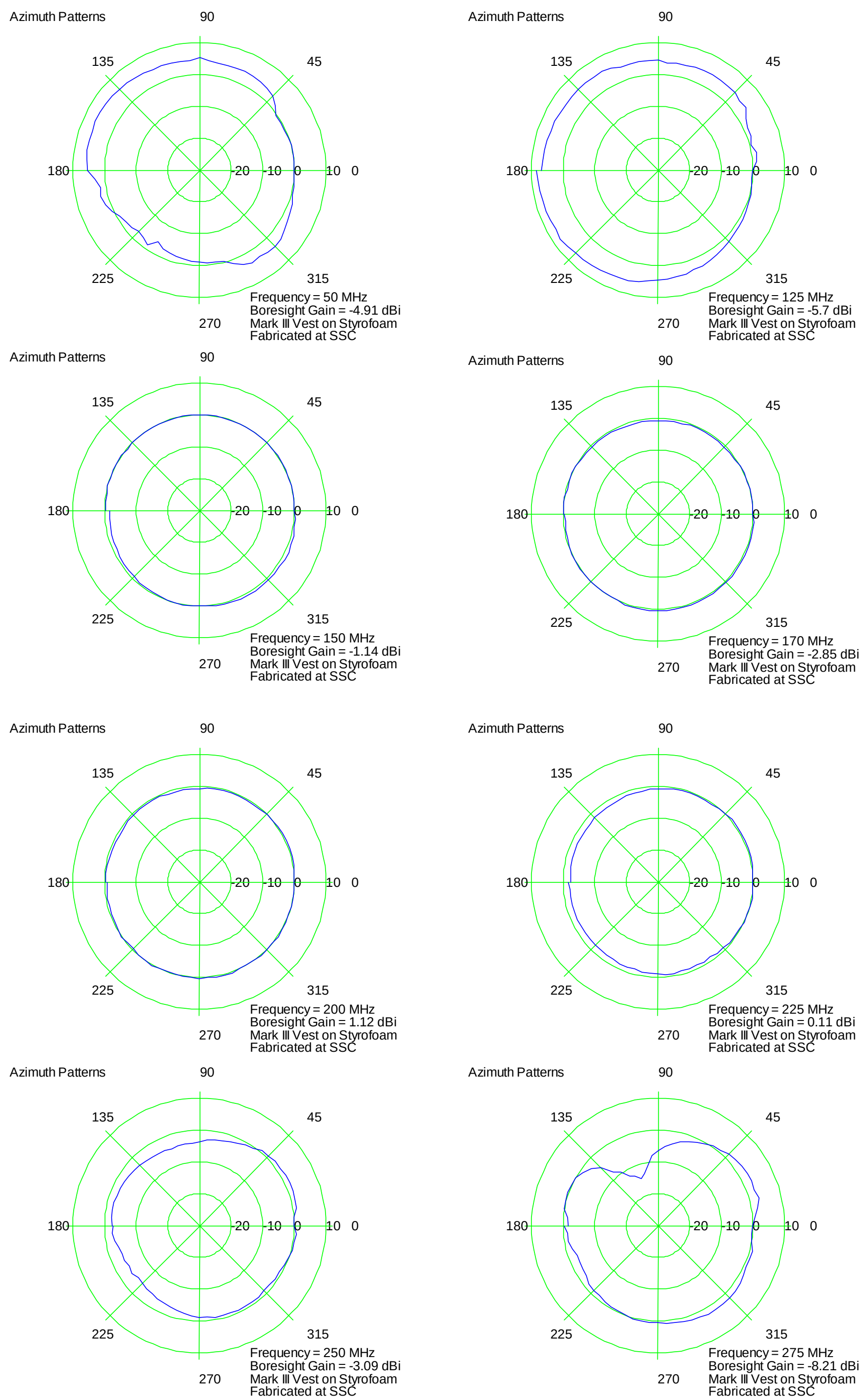


Figure 23. Radiation patterns versus azimuth angle normalized to boresight for 11 frequencies. Frequencies are 50, 125, 150, 170, 200, 225, 250, 275, 300, 350, and 400 MHz. All vest antennas become electrically large and exhibit nulls at frequencies higher than 250 MHz.

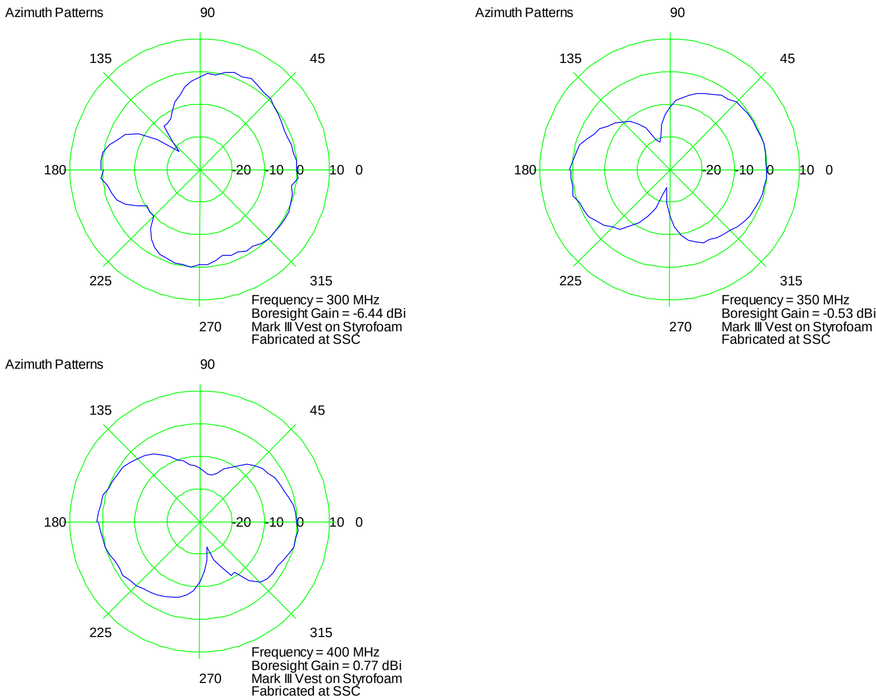


Figure 23. (continued) Radiation patterns versus azimuth angle normalized to boresight for 11 frequencies. Frequencies are 50, 125, 150, 170, 200, 225, 250, 275, 300, 350, and 400 MHz. All vest antennas become electrically large and exhibit nulls at frequencies higher than 250 MHz.

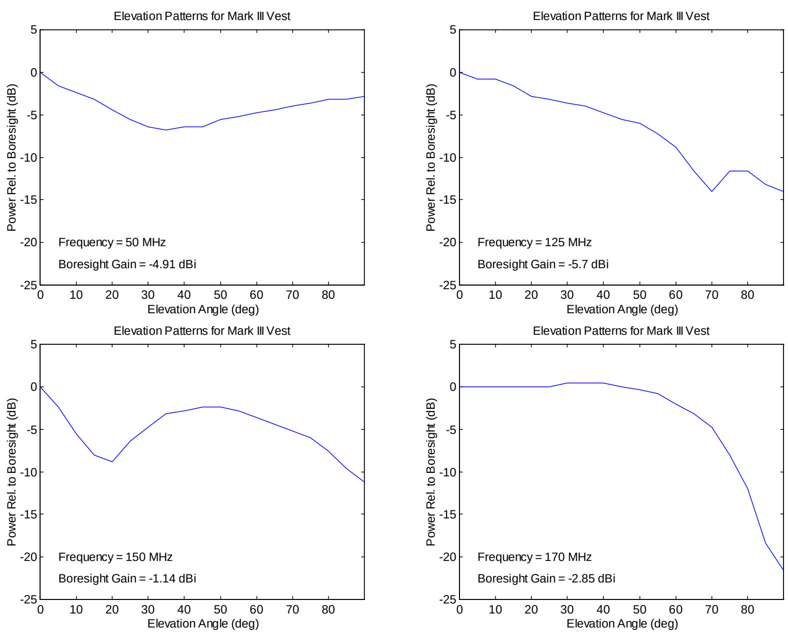


Figure 24. Elevation patterns at boresight azimuth for same 11 frequencies above. For many frequencies in UHF range, maximum of elevation angle does not occur at horizon.

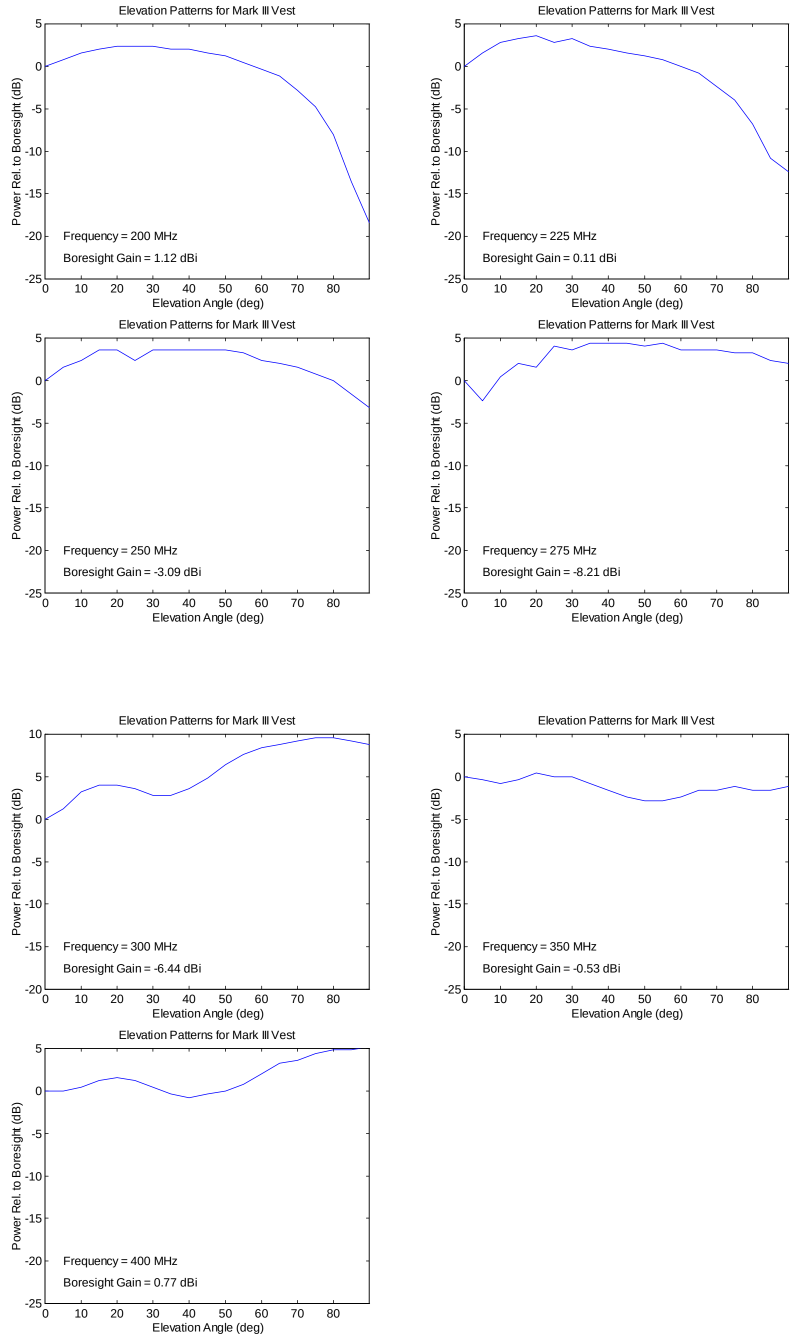


Figure 24 (continued). Elevation patterns at boresight azimuth for same 11 frequencies above. For many frequencies in UHF range, maximum of elevation angle does not occur at horizon.

Helmet Antenna

Based upon the advances of the Mark III vest antenna that symmetry and its controlled breaking implied, the SSC San Diego Model Shop fabricated the Mark III helmet antenna. Empirical studies of the VSWR versus frequency in the 500- to 1200-MHz range indicated that placing a second shorting strap at the 2 o'clock position would improve the matching. The feed was placed at a 6 o'clock position and the first shorting strap at noon. This asymmetric placing of a second shorting strap improved the helmet's effectiveness, even in frequencies as high as 2400 MHz. The widths of the upper and lower strips of FLECTRON were equal. The antenna was open at the top unlike the first two versions. A capacitor of 7.5 pf was placed in series with the feed to improve the matching further.

Figure 25 shows the front view of the Mark III helmet antenna. A second shorting strap was placed asymmetrically to improve matching. Figure 26 shows the rear view of the helmet antenna. The 7.5-pf capacitor was placed in series with the feed.

Figure 25. Mark III helmet antenna (front view)

Figure 26. Mark III helmet antenna (rear view).

Figure 27 shows the VSWR versus frequency of two identical models of the helmet antenna. For one of these antennas, the VSWR is less than 3:1 for all frequencies between 440 and 2310 MHz.

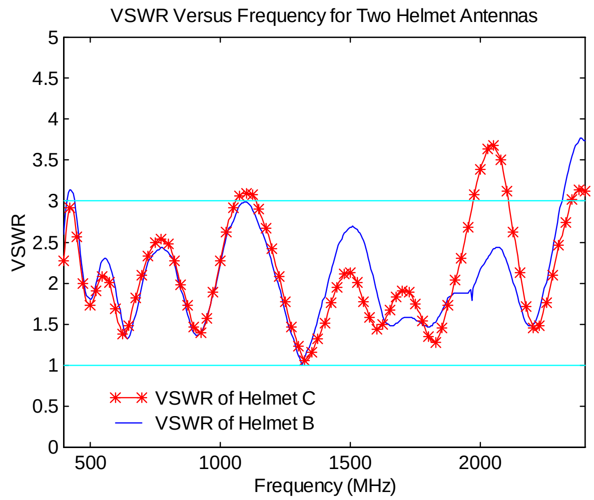


Figure 27. VSWR versus frequency for two identical models of Mark III helmet antenna. Each has a 7.5-pf capacitor in series.

Measurements were made in the anechoic chamber of SSC San Diego (Building 377). The measurements included boresight gain and radiation patterns in the azimuth and elevation direction. The transmit antenna was a wideband vertical dipole. A Mini-Circuits® low-noise amplifier increased the level of the received power by 30 dB. The log-periodic antenna already mentioned provided the reference for determining gain. Figure 28 shows the gain in the vertical and horizontal directions for the Mark III helmet antennas for frequencies between 400 and 1800 MHz. Only the gain at the boresight azimuth was measured. The gain has a local maximum of -5 dBi at a frequency of 2400 MHz. Since vertical and horizontal gains were approximately equal at frequencies near 500 MHz, proper phasing of signals could allow a circularly polarized signal to be transmitted efficiently.

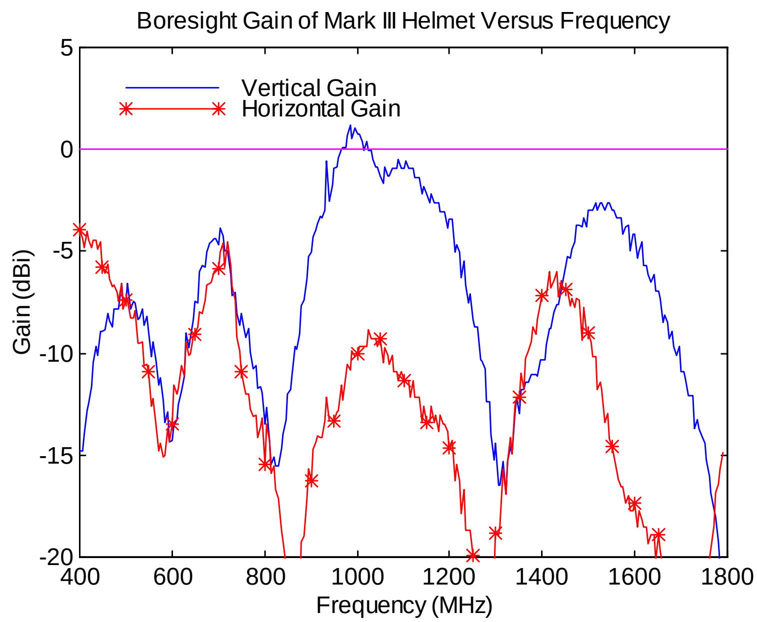


Figure 28. Boresight gain in vertical and horizontal directions as a function of frequency.

The boresight gain in vertical and horizontal polarizations was measured at 50-MHz increments for two helmet antennas sold to the U.S. Army Communications and Electronics Command (CECOM) in Fort Monmouth, NJ. The highest frequency at the measurement was 2400 MHz to accommodate the 802.11b protocol measurements described below.

Figure 29 shows the plot at the boresight gain versus frequency for these two helmet antennas versus frequency. The transmitting antenna was vertically polarized. These gain measurements were compared to the Mark III helmet antenna retained by SSC San Diego. The gain remains excellent, even to 2400 MHz. Figure 30 shows similar data for horizontal polarization. The helmet antenna is primarily vertically polarized for frequencies higher than 1000 MHz. A Kevlar helmet supported the antennas.

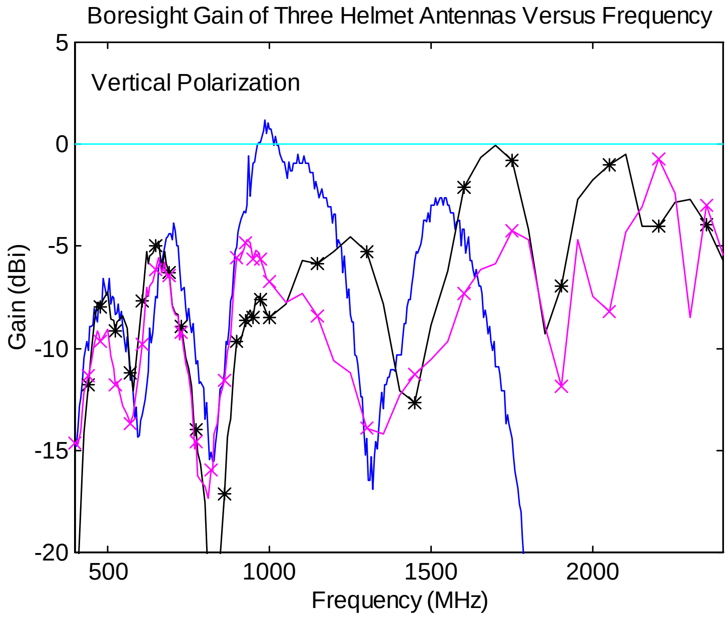


Figure 29. Boresight gain of three helmet antennas versus frequency. Transmitter had vertical polarization.

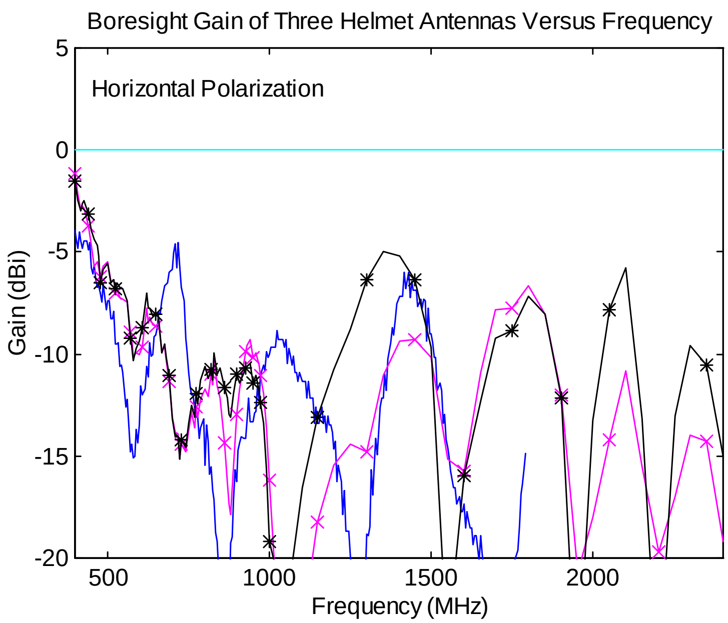


Figure 30. Boresight gain of three helmet antennas versus frequency. Transmitter had horizontal polarization.

Figures 31 and 32 present the azimuthal and elevation patterns of the helmet antenna for 14 frequencies. The frequencies increase from 500 to 1800 MHz in steps of 100 MHz. Similar to the vest antenna, the helmet antenna becomes electrically large as the frequency increases. The numbers of lobes and nulls in the pattern in the horizontal plane increase. The number increases from one shallow null at a frequency of 500 MHz to eight deep nulls at a frequency of 1800 MHz. The asymmetry from front to back of the helmet is the reason for the large number of nulls.

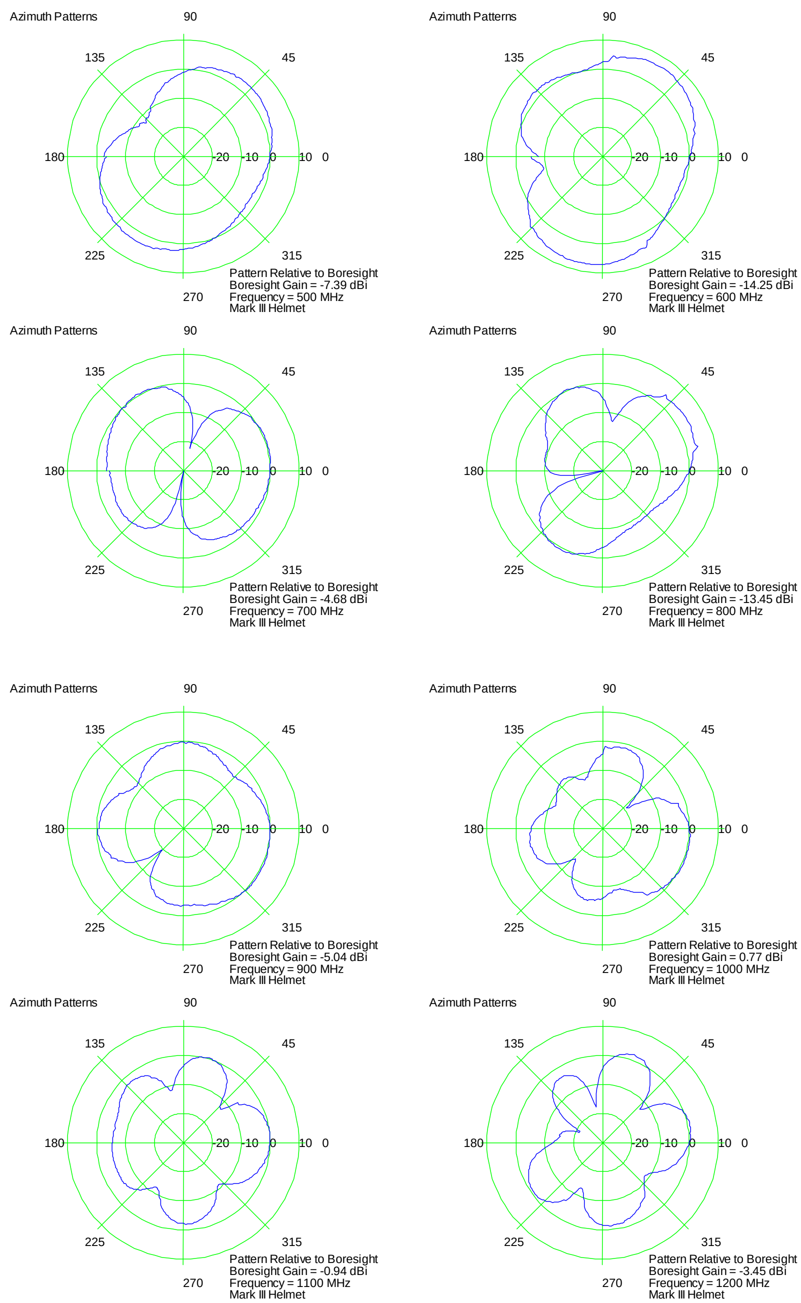


Figure 31. Radiation patterns in horizontal plane for Mark III helmet antenna for 14 frequencies. Frequencies increase from 500 to 1800 MHz in 100-MHz steps.

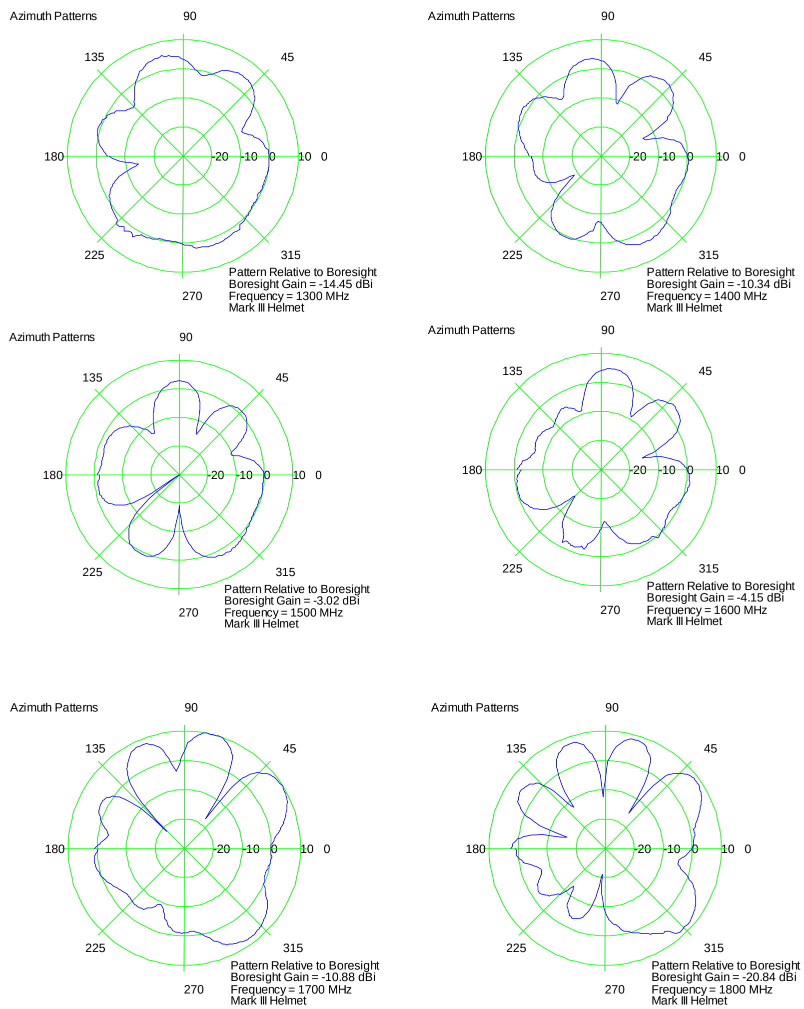


Figure 31 (continued). Radiation patterns in horizontal plane for Mark III helmet antenna for 14 frequencies. Frequencies increase from 500 to 1800 MHz in 100-MHz steps.

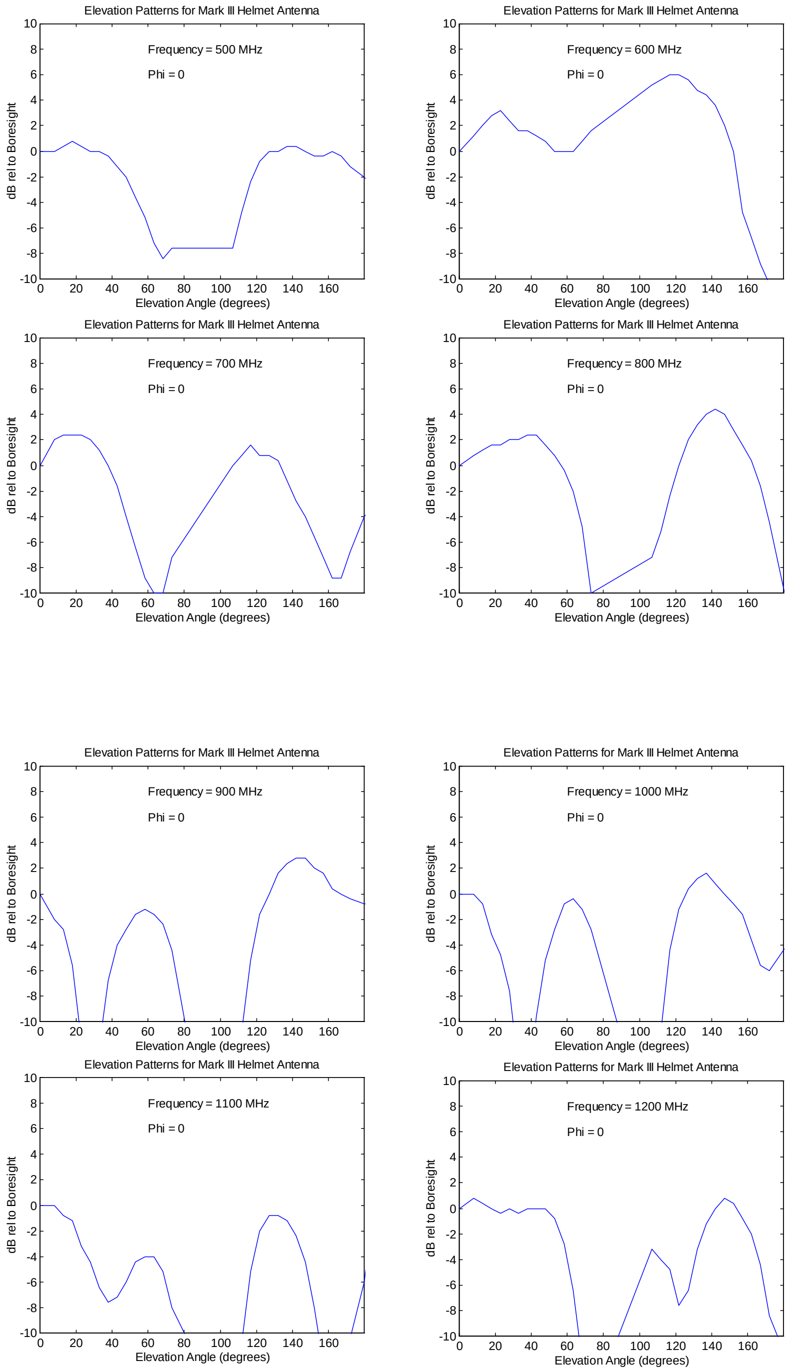


Figure 32. Elevation patterns at boresight elevation for Mark III helmet antenna. Frequencies are same as Figure 31.

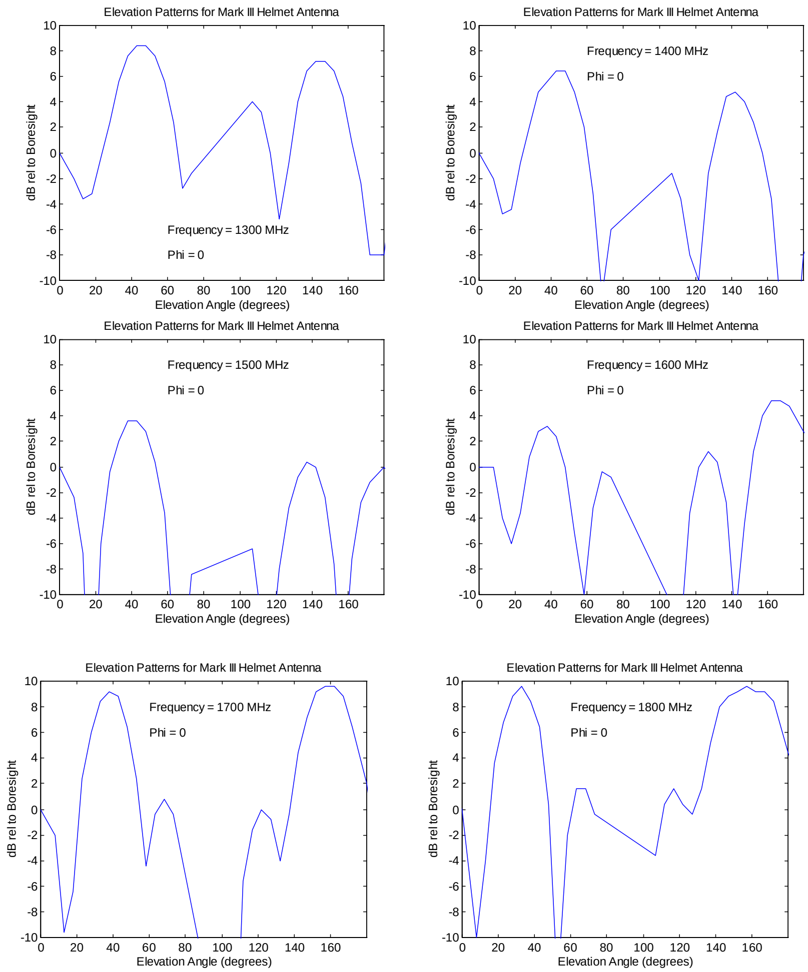


Figure 32 (continued). Elevation patterns at boresight elevation for Mark III helmet antenna. Frequencies are same as Figure 31.

To determine whether the helmet antenna would work to receive and transmit signals when worn, ICOM radios were used at less than 1-W power. At a distance of 6.2 km (the distance between Point Loma and the Silver Strand State Beach on Coronado), two-way communications were successfully demonstrated. The frequency used was 1240 MHz.

On 18 June 2001, an experiment was conducted on the SSC San Diego Model Range. A camera facing the moving second hand of a clock sent a signal to a transmitter. Using 802.11b protocol, the transmitter sent the signal through a microstrip antenna to a second microstrip antenna inserted into a laptop computer. When the two microstrip antennas were close together, the image of the moving second hand of the clock was displayed on the screen.

When the link is firmly established, the bit error rate (BER) is low. The link can sustain a data transfer rate as high as 11 Mb/s. As the link starts to degrade with increasing distance, the BER increases and the data transfer rate decreases. On the screen, the motion of the image of the clock begins to look jerky. Instead of moving at 1-s increments similar to old stop watches, the second hand moves at 5-s increments during the experiment. During the experiment at a distance of 5 m, the image of the clock moved at 1-s increments. As the distance increased to 30 m, the image moved at 5-s increments. By a distance of 60 m, the motion stopped completely. Eventually, the screen went black. On the microstrip antenna, there is a port for inserting a pin attached to a cable terminated with a subminiature version A (SMA) connector. At a distance of 60 m from the transmitter, the cable from the helmet antenna was connected to the cable and the laptop computer. The image of the moving second hand immediately restarted. The motion continued as the wearer of the helmet antenna moved to the edge of the model range. Later, measurements indicated that the distance between transmitter and the laptop computer was 160 m.

Whole-Body Antenna

Professor Lebaric suggested that the ground capacitively coupled to the antenna using metal inserts to the shoes could be used to complete the circuit for frequencies less than 30 MHz. Using the ground in this way would greatly increase the effective size of the antenna. Such an increase would lead to efficient (in the sense of low VSWR) operation in the 2- to 30-MHz range, providing the third of the antennas necessary to satisfy the JTR requirements.

The SSC San Diego Model Shop attached a feed to two strips of FLECTRON taped onto a flak jacket. No damage was done to the flak jacket so that it could be returned. (In the real system, these strips would be sewn onto the inside of the outer covering of the flak jacket.) The strips of FLECTRON went down the left and right sides of the flak jacket and connected to similar strips down the legs of a pair of pants. These strips, in turn, connected to pieces of FLECTRON taped to the inner soles of a pair of sandals. The FLECTRON on the inside of the sandals was expected to couple to the ground capacitively. Figure 33 shows the connection of the stripes down the pants leg to the FLECTRON on the inner soles of the sandals.

Figure 33. Connection of metal stripes down pants legs to inner soles of sandals. Metal on inner soles couples to the ground capacitively to complete circuit. This connection makes an effectively large antenna, useful for efficient operation in the 2- to 30-MHz frequency range.

Because of the capacitive coupling, variations of the VSWR based upon standing on different surfaces were expected. Standing under a tree in which no large amounts of metal could be located should have the best matching. A ground plane should be somewhat worse. A sidewalk should be intermediate. Initial measurements indicated that a 4:1 RF transformer (Mini-Circuits, 1997) should provide an excellent match. Figure 34 shows the VSWR versus frequency of the whole-body antenna when standing on a sidewalk and a ground plane. The matching was excellent at all the frequencies.

These measurements were made shortly after the purchase of the S113B Anritsu Sitemaster™. This device, battery-operated and weighing only 4 lbs, has made many of the measurements possible. The device is a 1-port network analyzer that can measure the VSWR and impedance at up to 517 frequencies between 5 and 1200 MHz. For some of the work done on the helmet antenna above 1200 MHz, a Hewlett-Packard HP-8510C network analyzer was used. The HP-8510C was located in the basement of Building 382 at SSC San Diego.

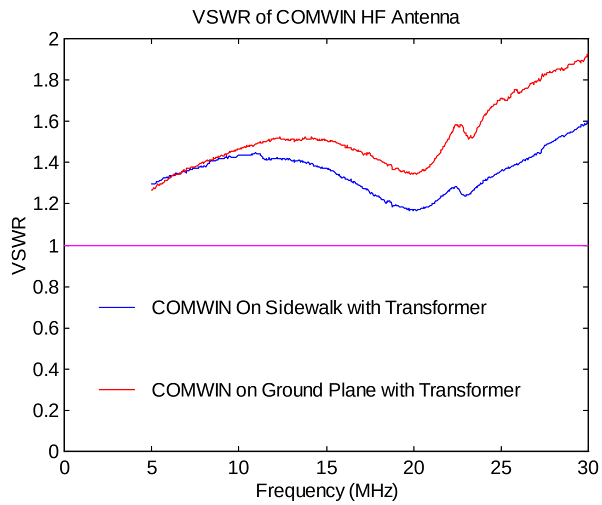


Figure 34. VSWR of whole-body antenna when standing on several different surfaces. A 4:1 RF transformer was inserted into the circuit to provide matching.

Figure 35 shows the gain of the whole-body antenna relative to a 35-foot whip measured while the wearer was standing on a ground plane. For most frequencies above 20 MHz, the whole-body antenna has a gain within 10 dB of the physically large antenna. The gain would probably improve by standing on a non-metallic surface such as grass.

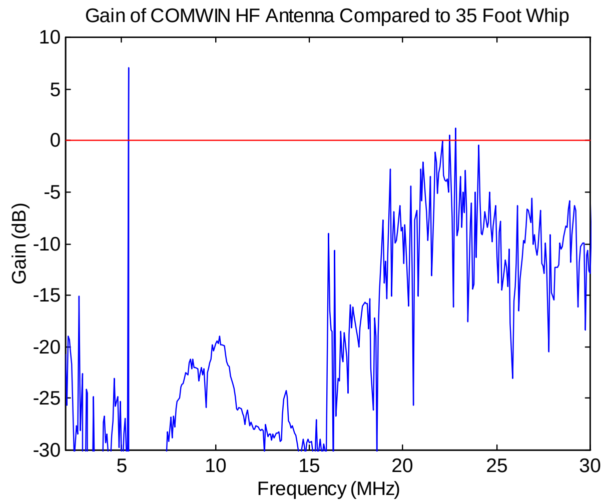


Figure 35. Gain of whole-body antenna compared to 35-foot whip. At frequencies greater than 15 MHz, the gains are comparable.

To demonstrate that the whole-body antenna was useful for long-range communications, station WWV, located in Boulder, CO, was used as a transmitter. Station WWV sends out a beep every second and the time in Greenwich, England, every minute at frequencies of 5, 10, 15, and 20 MHz. This signal is used for synchronizing the time of clocks and for testing high-frequency (HF) antennas. SSC San Diego used the WWV signal to demonstrate the effectiveness of the Mast Coupled Current Probe (MCCP) antenna. The whole-body antenna was connected to an HF receiver with audio capability. The sound of the beep was very clear at 10, 15, and 20 MHz. The sound was scratchy at 5 MHz. The signal level was a factor of 2 less than the current probe.

When this experiment was repeated on a ground plane and the shoes disconnected from the stripes down the pants, the signal disappeared. When done on a sidewalk, the signal remained even after the shoes were disconnected.

The RF transformer has a power rating of only 0.25 W. No attempt to use the whole-body antenna for transmitting a high-power signal was attempted. Radiation hazard considerations would probably preclude using such high-power signals.

Distribution System

The JTR is expected to output one signal at any frequency between 2 MHz and 2 GHz. Since no antenna can radiate efficiently over such a large frequency range, there must be some sort of distribution system. A switch provides such a device. An operator is needed to control which port is open. A triplexor would distribute the signal without operator input. With a triplexor, there must be “dead zones” at the borders between the frequencies at which the device sends the signal to one port or the other. A switch is a much simpler device. A triplexor will probably be used in the manufactured system.

Figure 36 shows a front view of the entire COMWIN antenna system with rotary switch on the wrist to control the distribution of signals from the radio to one of the three antennas. This system consists of the vest antenna (30 to 500 MHz), the helmet antenna (500 to 2500 MHz), and the whole-body antenna (2 to 30 MHz). Figure 37 shows a rear view showing the feed of the whole-body antenna. Below this feed is the SP3T switch controlled by the rotary switch on the wrist. Three 9-V batteries controlled by the rotary switch activated the appropriate SP3T port.

Figure 36. COMWIN antenna system (front view).

Figure 37. COMWIN antenna system (rear view).

If the helmet antenna is ever used in a deployed communications system, there must be a "break-away" connector. If the helmet falls off the soldier's head, the cable connected to the antenna must disconnect from the rest of the circuit. The connector that provides the interface between the SMA cable of the helmet antenna and the microstrip antenna inserted into the laptop provides one such device. The connector is easily pulled from the port in the microstrip antenna.

Figure 38 shows the VSWR versus frequency from 5 to 1200 MHz as port 1 (to the whole-body antenna), port 2 (to the vest antenna), and port 3 to the helmet antenna are opened in succession. The measurements were obtained in the SSC San Diego Model Shop. The Anritsu Sitemaster™ was used as the meter. For frequencies greater than 1200 MHz, the helmet antenna has demonstrated efficient operation. As Figure 38 shows, the VSWR of the system is less than 3:1 for all frequencies.

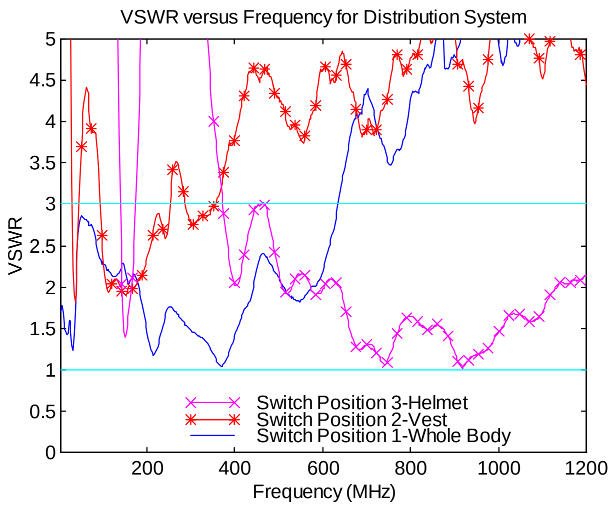


Figure 38. Plot of VSWR versus frequency for COMWIN system when ports 1, 2, and 3 of SP3T switch are opened in succession. At no frequency is the VSWR of COMWIN system greater than 3:1.

This experiment showed that the COMWIN antenna system provides a means to attain the 3:1 VSWR over the entire 2-MHz to 2-GHz frequency range.

Radiation Hazard Experiments

Many measurements were made of the electric field inside the empty vest. The change to the Mark III that has a capacitor in the matching circuit rather than a 2:1 transformer allowed much more power to be input. The transformer has a maximum rating of 0.25 W. The capacitor has a power rating in the kW range. Power as high as 400 W has been input into the vest antenna worn by a jell man. With such high power levels, the FLECTRON material becomes hot due to ohmic heating. Precautions must to taken avoid fire hazards. For power levels of the order of 5 W, such precautions are not needed.

Figure 39 shows a plot of the electric field when the input power was 5 W. Since the reflected power was not measured, there was no attempt to correct (increase) the electric field to consider this effect. This measurement shows that the height at which the maximum occurs is the one nearest the feed point. The field decreases uniformly with distance away from this height. At the height of the feed, the field is larger than the maximum permissible exposure (usually 61.4 V/m) for workers in a controlled environment. At all other heights, the field is less than the maximum permissible exposure for all frequencies.

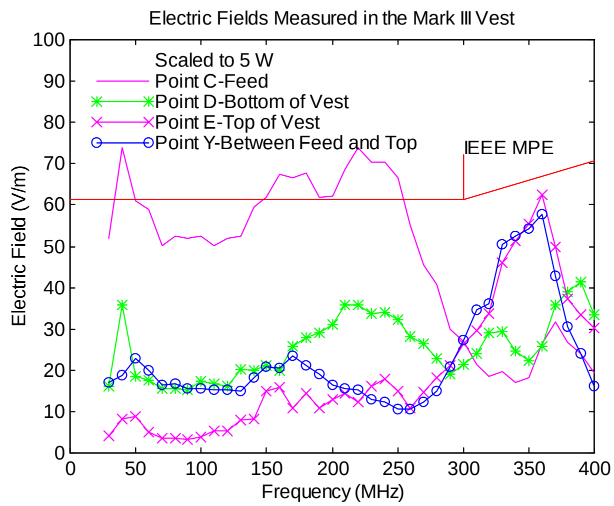


Figure 39. Electric fields measured for forward input power of 5 W. No attempt was made to measure or correct for reflected power from vest antenna.

An experiment was conducted at the Naval Health Research Center (NHRC) at Brooks Air Force Base in San Antonio, Texas, in mid-July 2001. The experiment used a sensor that measured the electric field when implanted into a jell man. Calibrated for cell-phone frequencies (900 and 1800 MHz), the NHRC workers attempted to measure the electric field at frequencies as low as 30 MHz. When implanted only 1 cm deep and 3 cm away from the feed, the sensor registered spurious signals. The wire attaching the sensor to the meter picked up the fields from the feed region outside the vest. Such probes should not be used at frequencies below 150 MHz (Chou et al., 1996).

Figure 40 shows photographs of the implantable E-field sensor. The photographs show the sensor when the cover is on and when the cover is off. The size of the sensitive area is about that of the tip of the index finger.

Figure 40. Implantable e-field sensor with cover on and off.

Figure 41 shows the locations of the measurement sites within the helmet antenna. One site is near the feed. A second site is in the center of the helmet. The third site is at the top of the helmet (shown at the bottom of the figure due to the helmet being upside down). Figure 42 shows the measurements of the electric field as a function of frequency for the three locations. Figure 43 shows the specific absorption rate data for the helmet antenna. The usual standard is that this quantity must be less than 0.4 W/kg averaged over the whole body. For isolated spots with a mass of 1 g, the specific rate can be as high as 8 W/kg. The specific absorption rate for the helmet antenna is less than 4 W/kg for all frequencies and locations. The rate usually less than 1 W/kg. Only near the feed where the measurements are suspect due to the influence of the high impedance wire does the specific absorption rate get large (3.1 W/kg) compared to the standard.

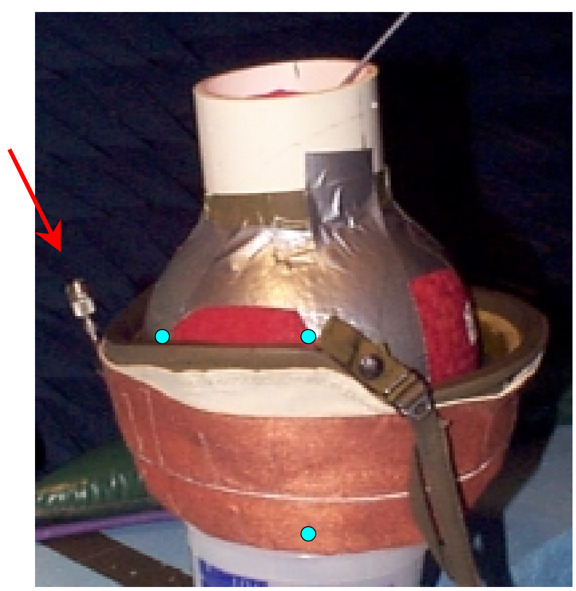


Figure 41. Measurement sites for implantable e-field probe in helmet antenna.

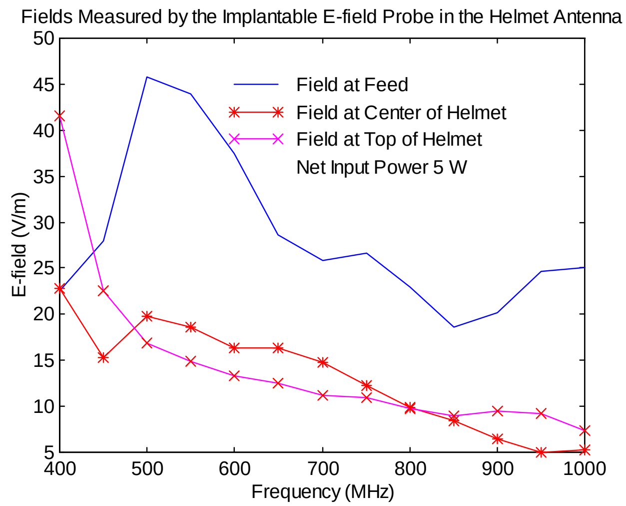


Figure 42. Measurements of electric field within helmet antenna as function of frequency. Input power was 5 W.

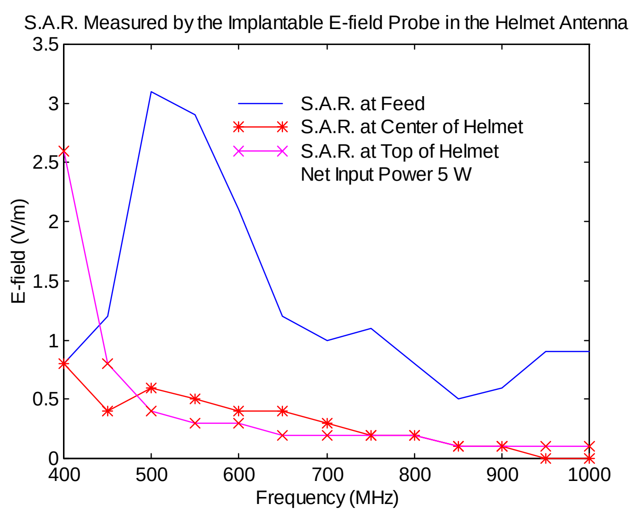


Figure 43. Measurements of specific absorption rate in W/kg versus frequency for three locations in helmet antenna.

The measurements of the electric field indicate that the helmet antenna probably meets the requirements for the maximum permissible exposure.

WORK DURING FY 2002

During FY 2001, a program manager signed on to become a transition sponsor for the vest antenna. Capt. Koby Moran of the Integrated Infantry Combat System agreed to do this. Capt. Michael Ferritto agreed to continue this sponsorship when he took over as program manager. Since there was a sponsor for one of the COMWIN antennas but not for the others, the emphasis was placed to bring the vest antenna forward for development.

The research done during FY 2002 consisted of resolving three issues. First, the radiation hazard identified during FY 2001 near the feed was mitigated. Mitigation involved much research, many measurements, and a close relationship with the workers at the NHRC. The work culminated in a test to certify that the vest antenna meets the radiation hazard requirements under most conditions of input power, frequency, and mode of use. Second, the vest antenna was used with radios to show how well they work together. The quality of communication is important. Finally, research was done on how to make the vest antenna more rugged. Research is needed on waterproofing the metal, using material impervious to water as backing for the FLECTRON, and making the feed less vulnerable to breakage.

TESTING WITH RADIOS

The PRC-148 is a hand-held radio manufactured by RACAL (now Thales) that is capable of transmitting or receiving a signal at any one of many pre-programmed frequencies in the VHF/UHF range. Since the radio can use hopping in frequency according to classified sequences and interfaces with cryptological units, the devices are under the control of CMS custodians. They must be locked in safes when not in control of the custodians. They can be taken off SSC San Diego only after permission has been granted. Their output power can be controlled. The maximum is 5 W. The power can be reduced to 3, 1, 0.5, and 0.1 W.

The Frequency Coordinator of Southern California must approve the frequencies used. We were given 32 frequencies. Unfortunately, the six frequencies in the 30- to 88-MHz range were 60.9, 61.9, 62.9, 63.9, 64.9, and 65.9 MHz. The 63.9 MHz frequency was chosen. Of the 26 other frequencies, 9 were chosen. Table 2 shows the collection of frequencies used to conduct the tests.

Table 2. Frequencies allocated by Frequency Coordinator of Southern California.

Band Number	Frequency (MHz)
1	63.9
2	142.425
3	162.425
4	226.5
5	258.5
6	292.5
7	319.5
8	345.5
9	435.075
10	449.779

As we have described in the section on radio tests during FY 2001, the rugged terrain of Point Loma limited the LOS range. We used Mission Bay and San Diego Bay to attain greater distances.

Since the vest antenna had not been certified for safety, only the principal investigator, Richard Adams (RCA), was allowed to use it at full power (5 W). The other member of the radio team, Daryl Von Mueller (DWV) used other types of antennas. The primary one that DWV used during transmission across San Diego Bay was the log-periodic antenna used for determining gain of various test antennas. Although the log- periodic antenna has very poor gain for frequencies less than 100 MHz, the gain improves to 4.8 dBi at a frequency of 450 MHz. The gain at 60 MHz is -4.95 dBi and at 65 MHz is -4.10 dBi. The polarization of the log-periodic antenna was always vertical.

A preliminary experiment was conducted with DWV on the Ocean Beach Pier. RCA started from Mission Bay Park and moved north. The Mission Bay–Pacific Beach boardwalk was very convenient. There were numerous streets that end on the boardwalk. These could be charted and the distances from the transmission site determined using a hand-held GPS receiver. At the lowest frequency and a power level of 3 W, DWV broadcast the time every 2 minutes. RCA started at a distance of 1.2 km away and moved towards Pacific Beach. With the standard antennas and the COMWIN vest antenna, RCA heard clearly every broadcast by DWV. Similarly, DWV heard every one of RCA's broadcasts ("load and clear") independently of whether RCA was moving north or south. The experiment ended at Law Street, where the boardwalk ends. The maximum distance was 5.5 km.

On 11 February 2002, RCA took the PRC-148 radio to Coronado. DWV used the log-periodic antenna on the SSC San Diego Model Range in Point Loma. The log-periodic antenna was positioned within 10 m of the triaxial arch that is a prominent feature of the Model Range. The arch is visible on Coronado even without binoculars. Again, DWV broadcast the time every 2 minutes. RCA almost always heard the broadcast clearly. Clear broadcasts were only impossible when RCA moved behind very tall buildings. Going further south on Route 75 towards Mexico reestablished communications. Table 3 shows a listing of the distances and locations of the communications.

Table 3. List of times, locations, and distances for communications between Point Loma and Coronado using the COMWIN antenna.

Time	RCA location latitude 32º N+ minutes	RCA location longitude 117º W+ minutes	RCA altitude (feet)	Distance DWV-RCA meters	Qual RCA Rx	Qual DWV Rx	Notes
1054	40.514	10.411	30	7462	3	3	Parking lot near hotels
1056	40.459	10.318	30	7633	3	3	On beach
1058	40.490	10.284	30	7664	3	3	Go onto Route 75,beach restrict
1100	40.490	10.284	30	7664	3	3	Do 8 count, all clear
1102	40.516	10.211	30	7756	3	2	Close to hotel
1104	40.458	10.145	30	7888	3	3	
1106	40.383	10.062	30	8057	ns	ns	Behind hotel, near fence
1108	40.345	10.014	30	8151	2	2	SE on Route 75, far from hotel
1110	40.290	9.951	30	8278	2	2	
1112	40.229	9.881	30	8420	2	2	
1114	40.167	9.815	30	8558	2	2	
1116	40.099	9.756	30	8690	3	2	
1118	40.036	9.700	30	8815	3	3	
1120	39.971	9.642	30	8945	2	2	
1122	39.903	9.585	30	9076	2	2	
1124	39.839	9.537	30	9192	2	2	
1126	39.767	9.485	30	9321	2	2	
1128	39.694	9.432	30	9452	2	2	
1130	39.624	9.381	30	9580	2	1	DWV Rx had much static
1132	39.554	9.333	30	9703	2	2	
1134	39.484	9.289	30	9822	2	2	Turn back go NW, do 8 count
1136	39.551	9.331	30	9709	2	2	Static not very bad
1138	39.596	9.361	30	9630	2	2	NW on Route 75
1140	39.658	9.407	30	9516	1.5	1	Much static
1142	39.727	9.457	30	9391	3	2	RCA Rx better than DWV
1144	39.799	9.509	30	9262	3	3	

Table 3. List of times, locations, and distances for communications between Point Loma and Coronado using the COMWIN antenna. (continued)

Time	RCA location latitude 32 deg N+ minutes	RCA location longitude 117 deg W+ minutes	RCA altitude (feet)	Distance DWV-RCA meters	Qual RCA Rx	Qual DWV Rx	Notes
1146	39.873	9.583	30	9101	2	2	
1148	39.941	9.619	30	8999	2	2	
1150	40.010	9.678	30	8865	2	2	
1152	40.078	9.738	30	8730	2	2	
1154	40.147	9.798	30	8596	2	1	
1156	40.198	9.847	30	8491	2	1	
1158	40.257	9.916	30	8351	2	2	Getting near hotels
1200	40.317	9.983	30	8214	2	1.5	DWV Rx had much static
1202	40.373	10.051	30	8079	2	1.5	
1204	40.428	10.116	30	7949	1.5	0	Very close to hotels
1206	40.482	10.177	30	7827	1.5	0	
1208	40.535	10.239	30	7704	2	2	Past one hotel
1210	40.584	10.310	30	7570	1	0	Broken voice
1212	40.555	10.371	30	7496	0	0	
1214	40.529	10.428	30	7428	3	3	On beach

Notes on Table 3

Date	02/11/2002	Quality	ns = no signal	Power
RCA Ant	COMWIN		0 = unintelligible	DWV 3 W
DWV Ant	LP		1 = barely intelligible	RCA 3 W
DWV latitude	32º N+ 41.838		2 = intelligible with static	
DWV longitude	117º W+ 14.923		3 = clear	
Frequency	63.9 MHz			

Attempts to continue walking on the beach were thwarted by an armed sailor who explained politely but firmly that walking on the Naval Amphibious Base was forbidden.

An experiment was conducted to determine the effectiveness of the COMWIN antenna over frequency. A figure of merit was the lowest power at which communications were still clear. Accordingly, once communications were established at a power level of 5 W, the power was reduced to 3, 1, 0.5, or 0.1 W or until communications were broken off.

One maneuver done to establish the effectiveness of the antenna was for RCA to rotate at 45° increments while DWV counted slowly to 8. Similarly, RCA rotated, transmitted, and counted to 8.

Table 4 shows a summary of the results. The distance between RCA and DWV remained constant at 6.2 km.

For two frequencies (63.9 and 142.425 MHz), RCA was face down on the sand. For several orientations there was two-way communication for a radio power of 5 W.

Table 4. Summary of results for radio tests.

Qual RCA Rx	Qual DWV Rx	Notes	Freq (MHz)	Power (W)
3	3	Eight count, rotated	63.9	5
3	3	RCA horizontal	63.9	5
2	2	Eight count, rotated	63.9	3
2	2	Eight count, rotated	63.9	1
2	2	Eight count, rotated	63.9	0.5
2	2	Eight count, rotated	63.9	0.1
3	3	Eight count, rotated	142.4	5
2	2	Eight count, rotated	142.4	3
2	2	Eight count, rotated	142.4	1
2	2	Eight count, rotated	142.4	0.5
2	1	Eight count, rotated	142.4	0.1
3	3	Eight count, rotated	162.4	5
3	3	Eight count, rotated	162.4	3
2	2.5	Eight count, rotated	162.4	1
2	2	Eight count, rotated	162.4	0.5

Table 4. Summary of results for radio tests. (continued)

Qual RCA Rx	Qual DWV Rx	Notes	Freq (MHz)	Power (W)
2	1	Eight count, rotated	162.4	0.1
3	3	Eight count, rotated	226.5	5
2	2.5	Eight count, rotated	226.5	3
2	2.5	Eight count, rotated	226.5	1
2	2.5	Eight count, rotated	226.5	0.5
1.5	2	Eight count, rotated	226.5	0.1
3	2.5	Eight count, rotated	258.5	5
3	2.5	Eight count, rotated	258.5	3
2.5	2.5	Eight count, rotated	258.5	1
2.5	2.5	Eight count, rotated	258.5	0.5
2	2	Eight count, rotated	258.5	0.1
3	2	Eight count, rotated	292.5	5
3	2	Eight count, rotated	292.5	5
3	1.5	Eight count, rotated	292.5	3
2	0	Eight count, rotated	292.5	1
0	0	Eight count, rotated	292.5	0.5
0	0	Eight count, rotated	292.5	0.1
2.5	2	Eight count, rotated	319.5	5

Table 4. Summary of results for radio tests. (continued)

Qual RCA Rx	Qual DWV Rx	Notes	Freq (MHz)	Power (W)
2	2	Eight count, rotated	319.5	5
2	2	Eight count, rotated	319.5	3
0	0	Eight count, rotated	319.5	1
0	0	Eight count, rotated	319.5	0.5
0	0	Eight count, rotated	319.5	0.1
3	2	Eight count, rotated, hiss	348.5	5
3	2	Eight count, rotated	348.5	3
2.5	2	Eight count, rotated	348.5	1
2	2	Eight count, rotated	348.5	0.5
2	1	Eight count, rotated	348.5	0.1
3	2.5	Eight count, rotated	435.1	5
3	2.5	Eight count, rotated	435.1	5
2	2	Eight count, rotated	435.1	3
2	2	Eight count, rotated, hiss	435.1	1
2	2	Eight count, rotated, noise	435.1	0.5
2.5	2.5	Eight count, rotated, static	449.8	0.1

Table 4. Summary of results for radio tests. (continued)

Qual RCA Rx	Qual DWV Rx	Notes	Freq (MHz)	Power (W)
2.5	2.5	Eight count, rotated, hiss	449.8	5
3	2.5	Eight count, rotated	449.8	3
2.5	2	Eight count, rotated, noise	449.8	1
2	2	Eight count, rotated, noise	449.8	0.5
2	2	Eight count, rotated, static	449.8	0.1
2	1	RCA horizontal facing south	63.9	5
2	2	RCA horizontal facing west	63.9	5
2	1	RCA horizontal facing north	63.9	5
2.5	2.5	RCA horizontal facing north	142.4	5
1.5	0	RCA horizontal facing south	142.4	5
2.5	2.5	RCA horizontal facing east	142.4	5
2.5	2.5	RCA horizontal facing west	142.4	5

Notes on Table 4

Date	03/04/2002	Quality	NS = no signal
RCA Ant	COMWIN		0 = unintelligible
DWV Ant	LP		1 = barely intelligible
DWV latitude	32º N+ 41.838		2 = intelligible with static
DWV longitude	117º W+ 14.923		3 = clear
Frequency	various MHz		

These tests show that the COMWIN vest antenna can provide effective voice communications over a very broad band.

There was one more test of the effectiveness of the COMWIN vest antenna. SSC San Diego sold two Mark III vest and helmet antennas to the U.S. Army Communications and Electronics Command (CECOM) in Fort Monmouth, NJ, during September 2001. These antennas were tested at the Electronics Proving Ground at Fort Huachuca, AZ, mid-June 2002. RCA and DWV attended the tests. RCA wore the vests during radio tests, radiation pattern determination, and VSWR measurements. Unfortunately, there was no standard antenna with which determine absolute gain. CECOM has not released the official results.

A network analyzer measured the transmission (S12) at 15-MHz increments as the COMWIN vest antenna either worn by a person or on a mannequin rotated on a turntable at 15° increments. To determine radiation patterns, the results versus azimuth angle were plotted as a function of frequency rather than as a function of frequency at an azimuth angle.

One factor was evident from the measurements. At least in the UHF band (225 to 400 MHz), the person inside the vest reduced the gain at the horizon compared to that of the vest on a mannequin. The reduction of gain can be as large as 20 dB. This serious deficiency must be solved.

The COMWIN vest antenna was used during radio tests in single-channel and frequency-hopping modes. Two types of radios capable of frequency hopping using the SINCGARS waveform were used during the test. One radio was the PRC-148. While another worker wore the COMWIN vest antenna in receive mode, the vest worn by RCA was used for transmission. Communications in the frequency-hopping mode were established at distances of 2 km. The input power was 5 W. Such a short range at high power was a reflection of the reduction in gain when a person wore the vest antenna. Work must be done to correct this deficiency.

There is a discrepancy between the results from Fort Huachuca and the radio results in Point Loma. The gain at UHF is low. The results from Fort Huachuca are consistent with those plotted in Figure 21 for boresight gain. On the other hand, there was effective communication over a distance of 6.2 km, even at UHF. There were two differences between the experiments.

The first difference was that DWV used a log-periodic antenna. The log-periodic antenna has poor gain (-4dBi) at frequencies less than 100 MHz, but increasingly good gain (up to 6.7dBi) for the higher frequencies. The second difference was that DWV was on Point Loma at an altitude of 100 m. Pattern lifting is a frequently observed phenomenon for electrically large antennas. This lifting must be investigated and corrected.

INVESTIGATING RADIATION HAZARD EXPERIMENTS

The impedance of the vest antennas worn by a person and an empty one were completely different. Fortunately, the scaling of the electric field with input power was demonstrated. A means for translating the measurements of the empty vest to the filled one was provided by a bi-directional coupler. By measuring the forward and reflected power and using the scaling of field to power, the electric field could be calculated for a net input power of 5 W.

The tests conducted at the NHRC in July 2001 indicated that there was a severe radiation hazard in the vest antenna at frequencies less than 100 MHz for an input power of 5 W. Tests conducted at SSC San Diego indicated that although there was a problem, the hazard was not severe. RCA had worn the vest antenna with input power levels as high as 5 W for hours at a time. In particular, the tests at Fort Huachuca took many hours over 2 days in temperatures as high as 108° F.

The unmodified Mark III COMWIN vest antenna does have a radiation hazard problem. Electric field leaks through the gap into the person. The conductivity of the person stops the fields from entering very deeply. The method of mitigating the radiation hazard involves absorbing or reflecting the energy that leaks in. Reflecting the energy has its own set of problems. The vest can become very narrow band if the reflection is not done cleverly. The gap can be shorted out.

Figure 44 shows the electric fields extrapolated from measurements conducted at SSC San Diego. The extrapolation consists of measuring the net power into the vest (the forward power was held constant at 5 W and the reflected power was measured). The electric field was assumed proportional to the square root of the net power. We then computed the field for 5 W of net input power. For frequencies less than 100 MHz, the measured field had to be multiplied by a factor as large as 3.

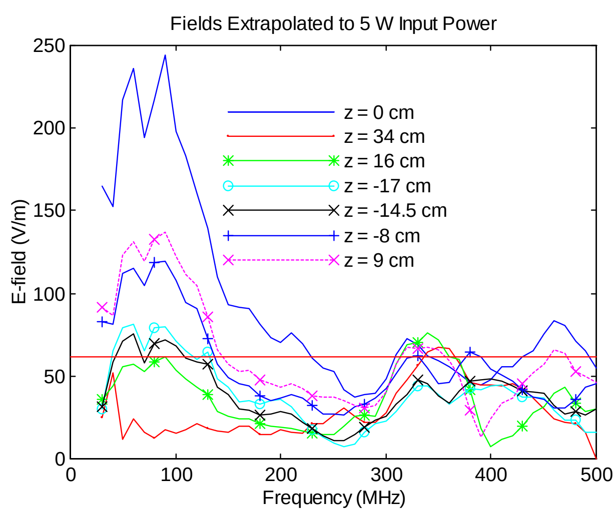


Figure 44. Fields inside Mark III vest antenna scaled to net input power of 5 W as function of frequency and position. Locations were always down center-line of vest. Heights indicated on the plot are relative to gap and feed.

Various modifications of the vest were tried. Containers of salt water of various concentrations were tried to determine whether a moderately conductive substance could absorb enough of the energy. Salt water was used due to cheapness and due to the fact that the conductivity could be modified easily within wide bounds. The salt water was held in tightly sealed plastic bags. The plastic bags were placed behind the feed in a small, cloth pocket. The attempt to absorb the energy with salt water failed. Too much energy still leaked into the vest.

Another modification was to pin one or more sheets of FLECTRON behind the pocket behind the feed. Although the FLECTRON would short the unmodified feed, the bags of salt water would absorb (hopefully) enough of the energy to prevent the shorting. This approach was not successful. Many combinations of FLECTRON and salt solutions were tried. Too much energy still leaked into the feed. The impedance changed in ways that indicate that the FLECTRON was shorting the feed.

The solution to the problem was anechoic foam. Produced by R and F Products in San Marcos, CA, this material absorbs energy in the GHz frequency range in anechoic chambers. The material is light but bulky. The purchaser can ask the manufacturer to modify the amount of carbon fiber. This modification tailors the degree of absorption. Although the absorption characteristics for frequencies as low as 30 MHz are almost never measured, this material even absorbs energy for the VHF range.

Figure 45 shows the electric field normalized for 5 W of net input power. The vest antenna was modified so that one or more thin sheets of anechoic foam were placed in the pocket behind the feed. Figure 46 shows the normalized electric fields for seven locations when one thick piece of foam was placed behind the feed and a thick strip was placed in the gap. The reduction in fields inside the vest was dramatic. Once the fields were absorbed, they could also be reflected by FLECTRON put behind the foam. The anechoic foam increased the matching, due to the loss of energy.

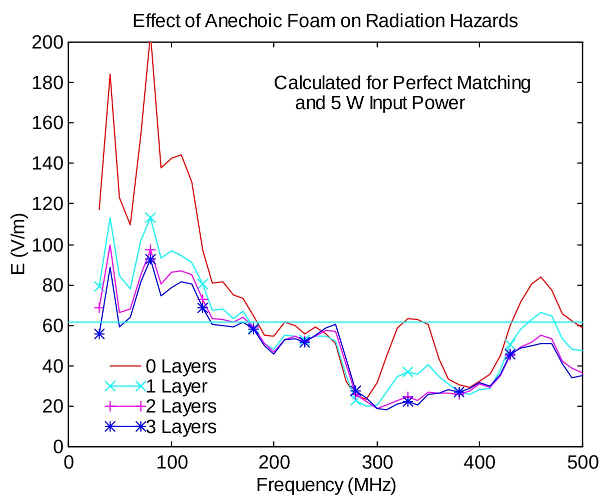


Figure 45. Electric field normalized to net 5 W of input power versus frequency. Effect of placing one, two, and three thin layers of anechoic foam in pocket behind feed is shown in decreasing fields inside the vest.

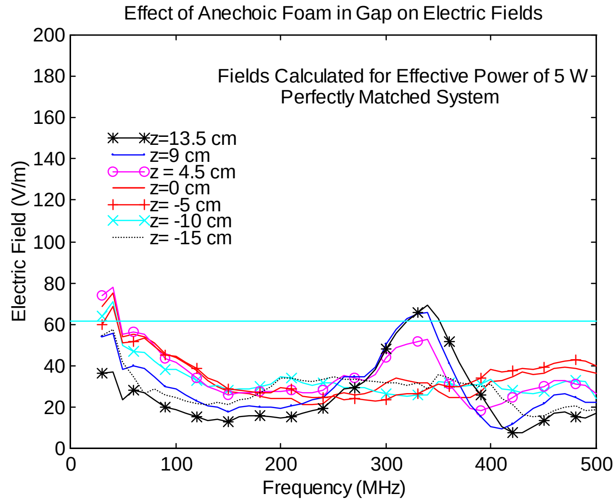


Figure 46. Electric field normalized to net 5 W of input power versus frequency and location within vest antenna. A thin layer of foam was placed in a pocket behind feed and a long strip of foam was placed in gap. Foam almost completely mitigates radiation hazard.

The anechoic foam works well at absorbing the energy. It is light, but bulky. Paul Schoen of the Naval Research Laboratory sent a sample of absorbing material. The material uses copper tubules (70 microns long and 1-micron-diameter, hollow cylinders of copper) embedded in urethane. Other material such as iron powder can be mixed into the substance before it solidifies. The material is used to isolate transmit and receive antennas on a decoy developed by the Australians. The material is denser than the foam, but much thinner and more flexible. The copper tubules could be used as a substitute for the anechoic foam.

Experiments were conducted at NHRC in late July 2002. NHRC has four implantable, non-conducting temperature probes and an automatic thermal monitoring system controlled by a laptop computer. The experiment consisted of monitoring the temperature for 5 minutes before input of power, recording the temperature for 5 minutes after application of power, and noting the temperature for 5 minutes after the input of power stopped. By using a bi-directional coupler and power meters that could record the difference between the two ports, the net power could be precisely determined. Large amounts of power were needed to ensure that the temperature rose rapidly on input of power. This setup removed the ambiguity of the cause of any temperature change. The slope of the temperature versus time curve was a measure of the specific absorption rate (SAR).

Before the experiment started, the vest antenna needed a minor modification. The antenna had a shorting strap made of FLECTRON. Various efforts to fold the antenna into suitcases over the previous 6 months led to kinks in the material. Upon input of 100 or 200 W of power, ohmic heating would concentrate at the kinks of the shorting strap. The material would overheat and the canvas backing would begin to burn (the vest did not pass the sniff test). The use of metal braiding between the top and bottom of the antenna acted as a shorting strap. This antenna was designed for input powers no higher than 5 W. This problem has not arisen at the 5-W power level.

NHRC also used an imaging infrared camera to record hot spots and the average temperature of the front of the vest. When 400 W was input into the vest, the threads and seams of the vest antenna became evident in the image.

There were six different antennas used during the set of experiments. Vest A and Vest B were almost identical. The only difference was that Vest B had pockets sewn behind the feed and in the gap. Vest C was the same as Vest B, only with anechoic material in the pocket behind the feed and in the gap. Vest D had the tubular composites from the NRL in the gap and behind the feed. Vest E differed from Vest D in having a different type of anechoic material. Vest F differed from Vest C in having FLECTRON backing the anechoic material, which reflected energy that had passed through the anechoic material. The matching of the antenna was excellent. For many frequencies, the percentage of power returned was less than 10%. A 10-dB return loss implies a VSWR of less than 2:1.

The specific heat of the jell man was approximately 3600 J/(°C-kg) [Reference Leonard, Foster, and Athey, 1984). The product of the specific heat and the slope of the temperature versus time curve was the power per unit mass that had gone into the body to heat it. This quantity is called the specific absorption rate (SAR). The maximum allowable SAR averaged over the entire body is 0.4 W/kg. For a 1-g cube, the SAR for a “hot spot” can be as high as 8 W/kg. The columns in Table 5 denote the net power and frequency of the input signal. The next four columns in Table 5 denote the temperature derivatives of the four probes. The next column in Table 5 shows the arithmetic mean of the four derivatives. The next to last column in Table 5 is derived by determining the maximum amount of power that can be input into the vest and still meet the SAR requirement. The formula for this purpose is $P_{max} = P_{net}/(150 * DT/dt_{ave})$. The temperature derivative is measured in units of °C/min.

Table 5. Determination of temperature derivatives and specific absorption rate for various vest antenna designs.

Net Power (W)	Freq (MHz)	DT/dt T1 (°C/min)	DT/dt T2 (°C/min)	DT/dt T3 (°C/min)	DT/dt T4 (°C/min)	DT/dt Average (°C/min)	Max Power (W)	Vest
50	40	0.0498	0.0566	0.0944	0.1009	0.0754	4.4	A
80	50	0.0196	0.0243	0.1130	0.0892	0.0615	8.7	A
100	60	0.0347	0.0461	0.1310	0.1267	0.0846	7.9	A
100	80	0.0419	0.0583	0.0343	0.0313	0.0414	16.1	A
80	71	0.0463	0.0499	0.0424	0.0469	0.0464	11.5	B
100	80	0.0410	0.0604	0.1035	0.1036	0.0771	8.6	B
100	30	0.0288	0.0244	0.0257	0.0149	0.0234	28.5	C
100	35	0.0418	0.0345	0.0201	0.0088	0.0263	25.3	C
100	40	0.0419	0.0437	0.0202	0.0063	0.0280	23.8	C
100	45	0.0598	0.0570	0.0132	0.0082	0.0346	19.3	C
100	50	0.0628	0.0761	0.0135	0.0160	0.0421	15.8	C

Table 5. Determination of temperature derivatives and specific absorption rate for various vest antenna designs. (continued)

Net Power (W)	Freq (MHz)	DT/dt T1 (°C/min)	DT/dt T2 (°C/min)	DT/dt T3 (°C/min)	DT/dt T4 (°C/min)	DT/dt Average (°C/min)	Max Power (W)	Vest
100	55	0.0816	0.0765	0.0302	0.0403	0.0572	11.7	C
100	60	0.0625	0.0679	0.0399	0.0332	0.0509	13.1	C
100	75	0.0199	0.0383	0.0060	0.0033	0.0169	39.5	C
200	75	0.2892	0.2093	0.0737	0.0971	0.1673	8.0	C
100	80	0.0631	0.0606	0.0176	0.0106	0.0380	17.6	C
200	75	0.1605	0.1568	0.0954	0.0844	0.1243	10.7	D
200	80	0.1460	0.1584	0.0639	0.0656	0.1085	12.3	D
200	75	0.1248	0.1551	0.0838	0.0799	0.1109	12.0	E
200	75	0.2610	0.1601	0.0289	0.0275	0.1194	11.2	F
400	80	0.6113	0.3906	0.0296	0.0473	0.2697	9.9	F

Table 5 shows that the anechoic material does much to mitigate the radiation hazard of the vest antenna. For most frequencies, more than 10 W can be input into the vest and still meet the SAR requirements. Since no more than 5 W is expected to be input, the vest antenna is probably safe.

Figure 47 shows the worst case of radiation hazard. When 50 W was input into Vest A for 5 minutes, the temperature on one of the probes increased by 0.5° C. Others increased somewhat less. Figures 48 through 56 present the temperature records for Vest C with anechoic material in the gap and behind the feed for different frequencies. Figures 57 and 58 show the temperature record when 200 W is input into the vest antenna with copper tubules in the gap and behind the feed. The frequencies were 75 and 80 MHz, respectively. Figures 59 and 60 show the temperature record when 200 and 400 W are input into Vest F with anechoic material and FLECTRON are behind the feed and in the gap at 75 and 80 MHz, respectively.

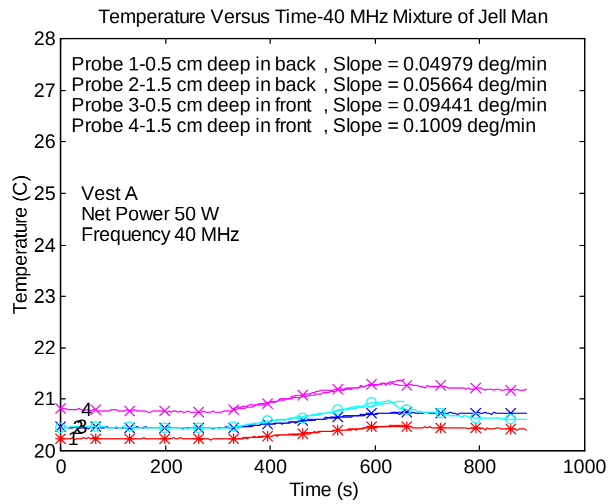


Figure 47. Temperature versus time for four probes when 50 W is input into Vest A at a frequency of 40 MHz.

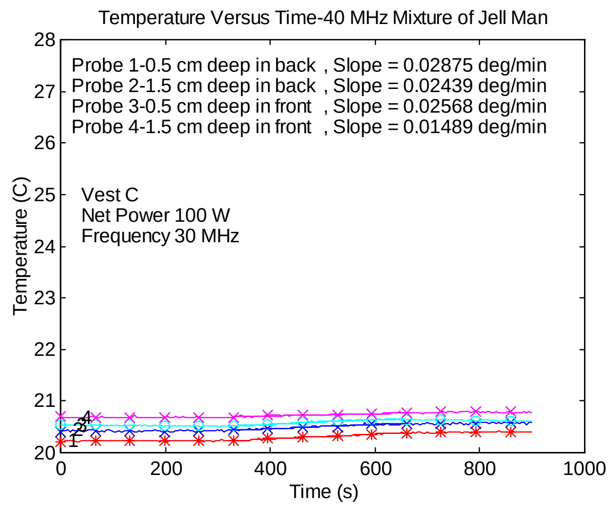


Figure 48. Temperature versus time for four probes when 100 W is input into Vest C at a frequency of 30 MHz.

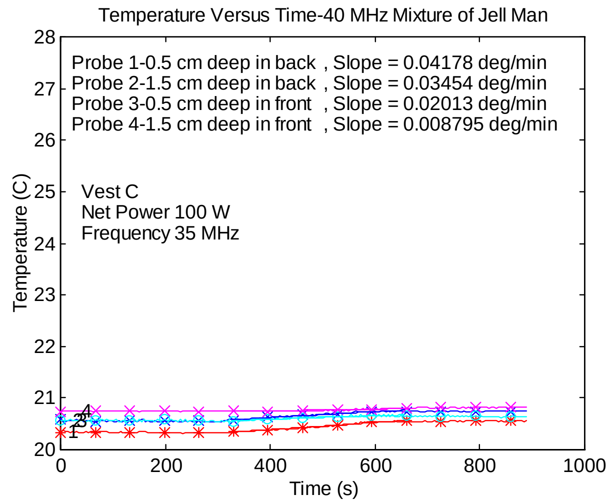


Figure 49. Temperature versus time for four probes when 100 W is input into Vest C at a frequency of 35 MHz.

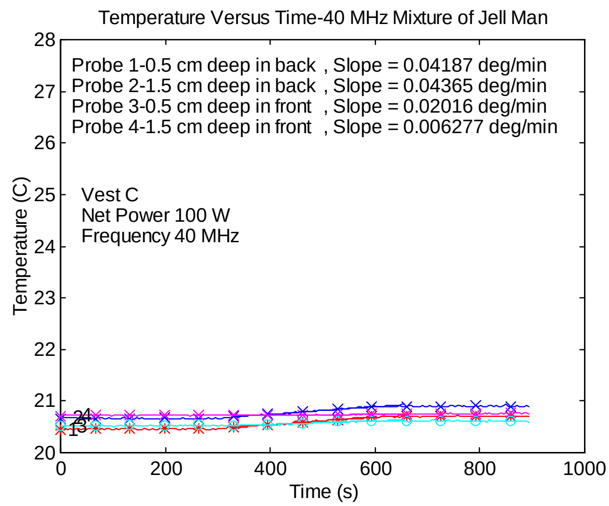


Figure 50. Temperature versus time for four probes when 100 W is input into Vest C at a frequency of 40 MHz.

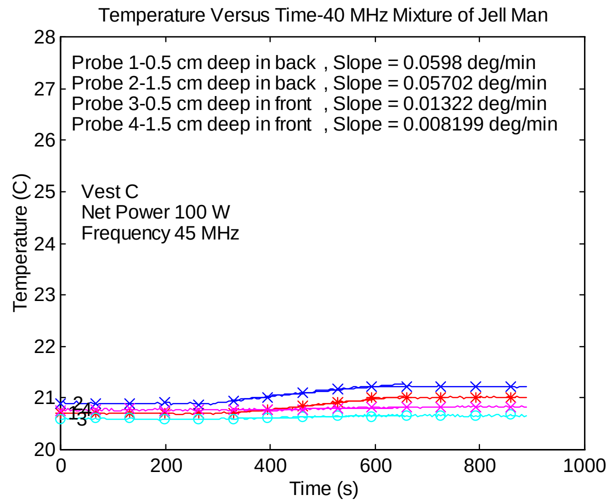


Figure 51. Temperature versus time for four probes when 100 W is input into Vest C at a frequency of 45 MHz.

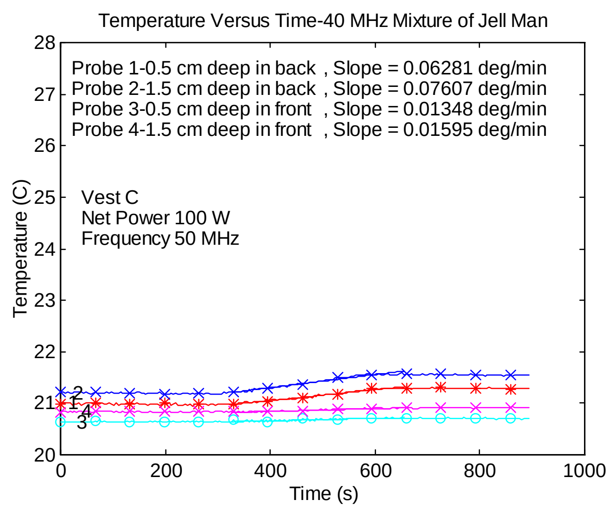


Figure 52. Temperature versus time for four probes when 100 W is input into Vest C at a frequency of 50 MHz.

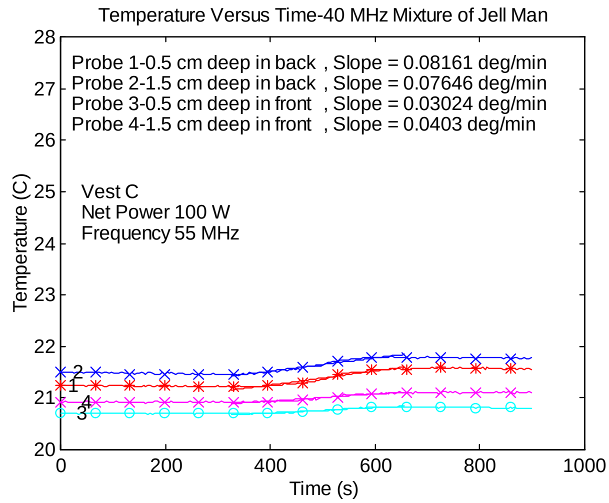


Figure 53. Temperature versus time for four probes when 100 W is input into Vest C at a frequency of 55 MHz.

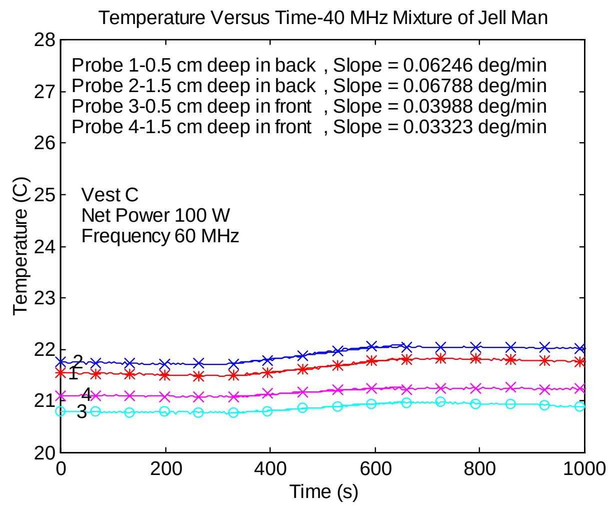


Figure 54. Temperature versus time for four probes when 100 W is input into Vest C at a frequency of 60 MHz.

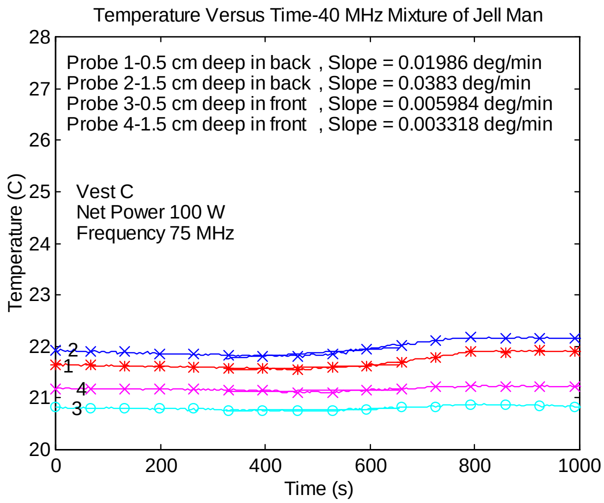


Figure 55. Temperature versus time for four probes when 100 W is input into Vest C at a frequency of 75 MHz.

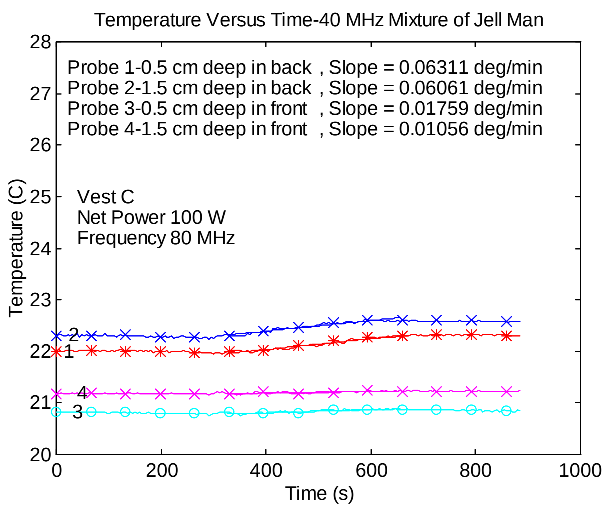


Figure 56. Temperature versus time for four probes when 100 W is input into Vest C at a frequency of 80 MHz.

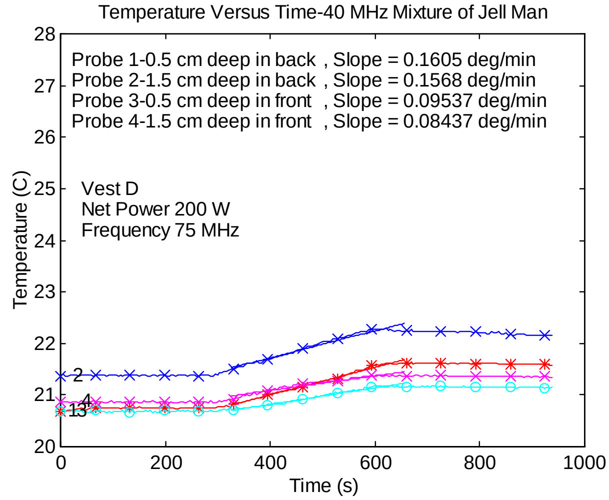


Figure 57. Temperature versus time for four probes when 200 W is input into Vest D (copper tubules behind feed and in the gap) at a frequency of 75 MHz.

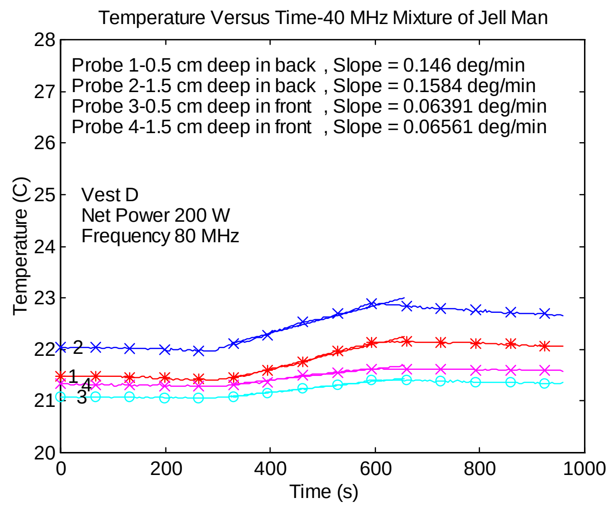


Figure 58. Temperature versus time for four probes when 200 W is input into Vest D (copper tubules behind feed and in the gap) at a frequency of 80 MHz.

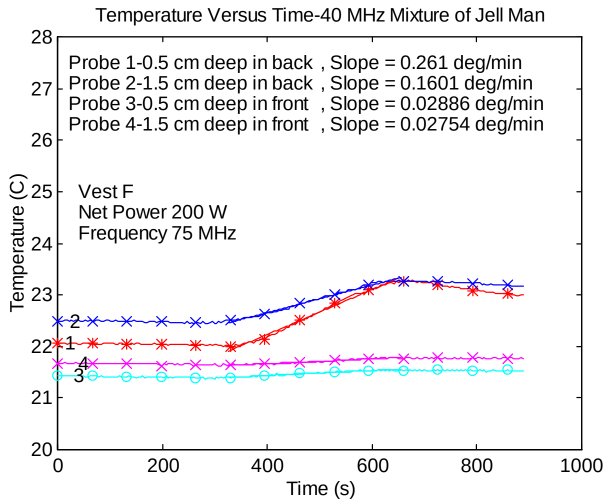


Figure 59. Temperature versus time for four probes when 200 W is input into Vest F (anechoic material backed by FLECTRON behind the feed and in the gap) at a frequency of 75 MHz.

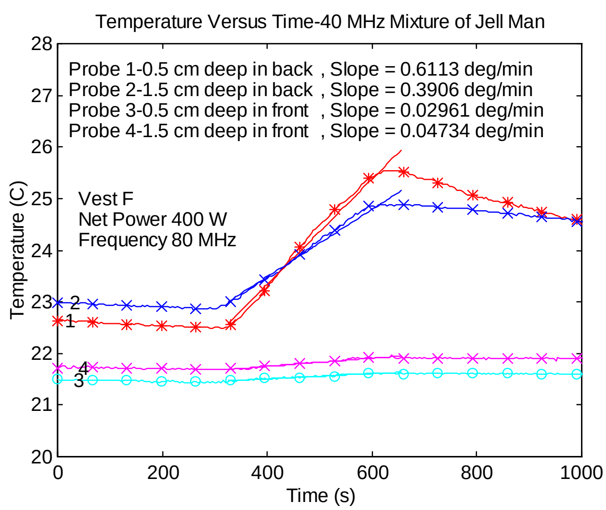


Figure 60. Temperature versus time for four probes when 200 W is input into Vest F (anechoic material backed by FLECTRON behind the feed and in the gap) at a frequency of 80 MHz.

As indicated by the table, many other cases were examined.

Further experiments were conducted at the NHRC from 10–12 September 2002. Most tests were conducted using the anechoic material backed by FLECTRON (vest F). Up to six temperature probes recorded the temperature rise in many places. Frequencies used varied from 30 to 90 MHz and from 225 to 450 MHz (a different composition of jell was used for the UHF measurements). The results will be published by NHRC in a report that will be submitted to Wayne Hammer at SSC Charleston.

Wayne Hammer is an authority on radiation hazard for the U.S. Navy. He is a certifying authority for sites. He will write a cover letter to the report certifying the conditions under which the

COMWIN vest antenna can be used safely. Preliminary indications for the vest antenna are that for a net power level of 5 W, the SAR level is less than 0.2 W/kg in the 30- to 90-MHz range.

One other measurement must be done to ensure that no hot spots were missed. In many radiation hazard measurements for determining site safety, a jell mannequin has been exposed to very high fields for a short time. When the input power was shut off, the jell mannequin was then placed inside a calorimeter. Over 48 hours, the temperature of the jell mannequin decreases to that of the ambient air inside the calorimeter. The slope of the temperature versus time is a measure of the SAR of the whole body (Olsen, 1982). As of September 2002, this measurement had not been done.

Theory

During FY 2000, there were many attempts to develop a theoretical model for the electric fields inside the empty vest. We used the method of moments that was accurate for predicting the impedance of the vest antenna. Unfortunately, the models used predicted that the fields would be much less than those measured. The field just outside the vest and close to the feed was used to normalize all results (the input power was a scaling factor that this method would remove as an independent parameter). The ratio predicted was a factor of 20 to 100 lower for the theoretical prediction than the measured value.

We turned to the method of finite difference time domain (FDTD). In solving a partial differential equation by numerical means, derivatives are approximated by finite differences, i.e., the ratio of differences of the dependent variable evaluated at two locations to the distance between the locations. Maxwell's equations are often solved in the frequency domain in which all time-dependence is assumed to be sinusoidal. In the FDTD method, Maxwell's equations are solved in the time domain. The initial values of all sources and fields are assumed to be zero. The sources increase as time progresses. The fields increase in response to the sources. This technique is often used for radiation hazard studies. Inhomogeneity of the material is easily handled as long as a Cartesian coordinate system is used.

If the material of the vest and the interior have properties that do not depend on frequency, a simple technique can be used to increase the speed of computation. The source can be assumed to be a sum of sinusoids and a fast Fourier transform technique can be used to compute the fields for many frequencies at once. The technique used in most studies is to take each calculation at one frequency. The process is time-consuming because the calculations for each frequency take a long time to complete. The most important aspect of this technique is ensuring that all calculations are linear. Non-linear processing typical of total field types of electric field sensors would make a Fourier transform inapplicable. The Fourier transform must be taken on the individual components of the electric field.

The electric field sensor used in the measurements is an example of a total field type. The sensor computes the magnitude of the field, i.e., the square root of the sum of the squares of the component. The measurement of the field is isotropic and not influenced by misalignment of the sensor because of this processing. Figure 61 shows the electric field sensor used. The including stand is approximately 31 cm. The sensitive area is a cylinder 10 cm high and 10 cm in diameter.

Figure 61. Isotropic electric field sensor used to make RADHAZ measurements inside vest antenna.

The sensitivity is excellent. Over the frequency range 10 to 1000 MHz, the minimum electric field detected can be as low as 0.5 V/m. Since fiber-optic cables connect the interface to the meter, there is less metal to disturb the measurement. High-impedance cable connects the sensor to the interface. The large size of the sensor implies great sensitivity and linearity, even for frequencies as low as 30 MHz. Since the field of the vest antenna is fairly large if the input power is more than 5 W, the signal-to-noise ratio of the measurement is expected to be high.

In comparing theory and experiment, there is one overall scaling factor. There is no good way to control the amount of power input to the model. The calculation assumes some initial voltage amplitude that multiples a sinusoidal time-dependence. The overall scale factor was determined by comparing the field measured outside the vest but close to the feed with that predicted theoretically. The comparison of the theoretical to experimental fields outside the vest permits the scaling factor to be determined. The theoretical fields must be divided by 9.23 to compare them to the experimental ones. Figure 62 shows the determination of the theoretical with the experimental result outside the vest.

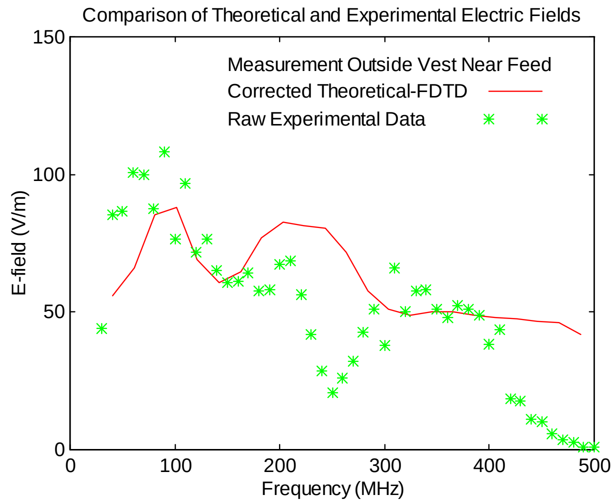


Figure 62. Comparison of theoretical with experimental results for fields just outside vest and close to feed. This comparison allowed a determination of overall scale factor used for other sites inside vest.

Figures 63 through 68 show the comparison between theory and experiment for the interior of the vest antenna. Only the overall scale factor determined in Figure 58 were used. The fields near the feed show the most inaccuracy. The comparison is usually reasonable if not entirely satisfactory. Further work to increase spatial resolution and improve accuracy is proceeding.

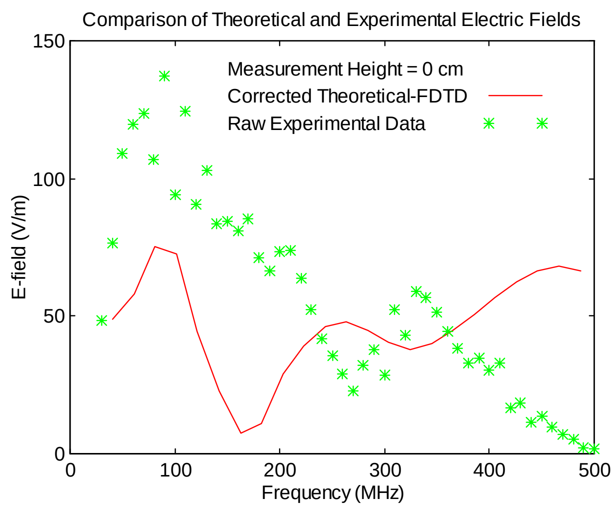


Figure 63. Comparison of theoretical with experimental results for the total field versus frequency. Height of measurement is equal to feed.

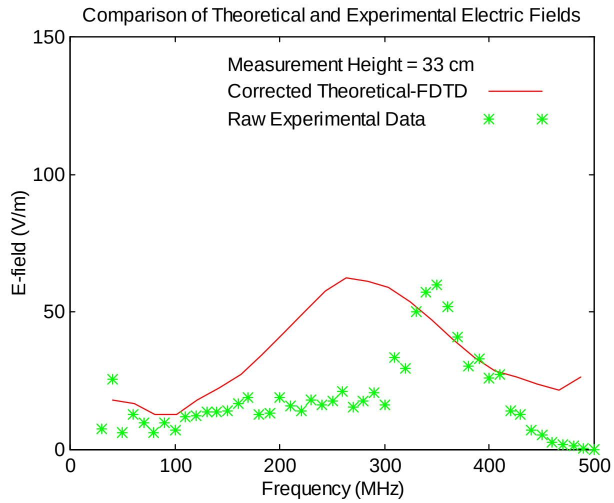


Figure 64. Comparison of theoretical with experimental results for total field versus frequency. Height of measurement is 33 cm above feed.

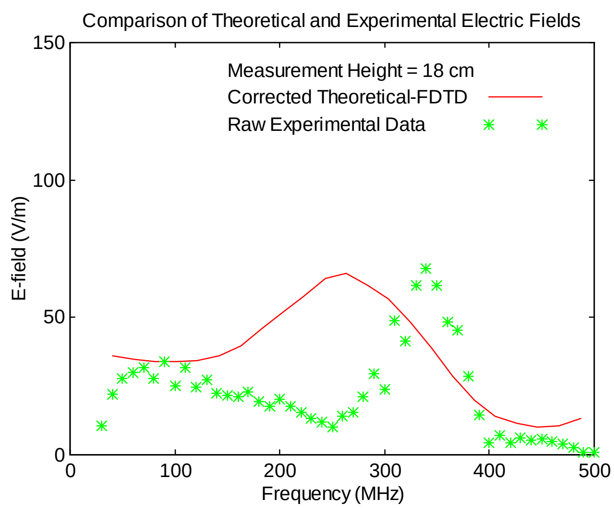


Figure 65. Comparison of theoretical with experimental results for total field versus frequency. Height of measurement is 18 cm above feed.

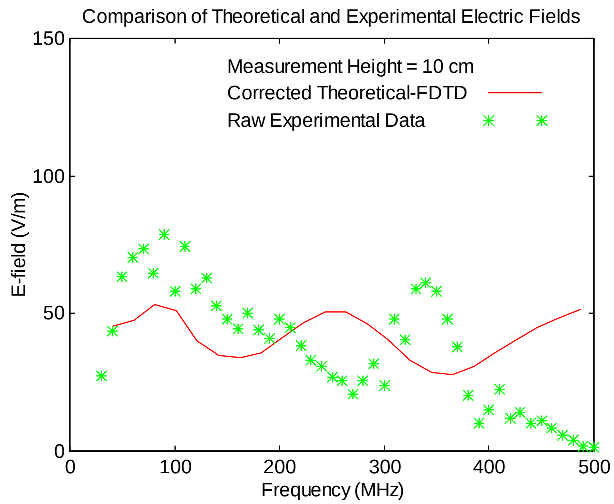


Figure 66. Comparison of theoretical with experimental results for total field versus frequency. Height of measurement is 10 cm above feed.

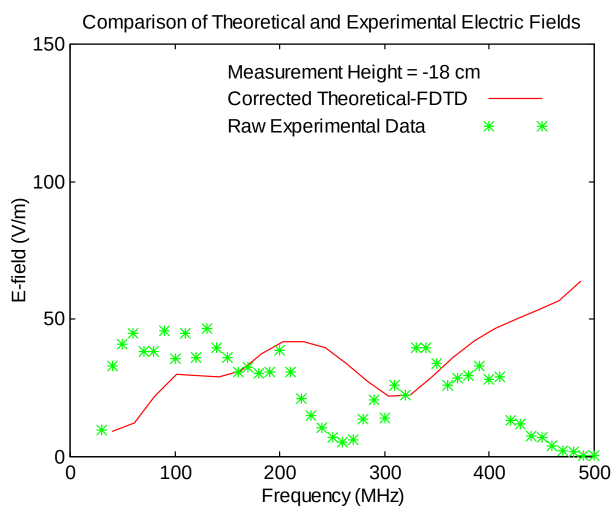


Figure 67. Comparison of theoretical with experimental results for total field versus frequency. Height of measurement is -18 cm below feed.

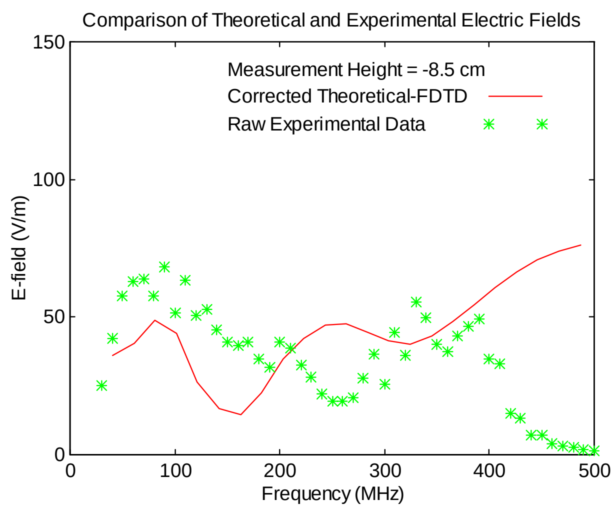


Figure 68. Comparison of theoretical with experimental results for total field versus frequency. Height of measurement is -8.5 cm below feed.

Figure 69 shows the theoretical results for the total field when the interior of the vest is filled with a conductive jell. The conductivity and relative dielectric constant were assumed independent of frequency and equal to 1 S/m and 55, respectively. This calculation indicates that if the jell extends only to the lowest edge of the vest, the fields below the vest might be large. This calculation also indicates a position at which temperature probes should be placed.

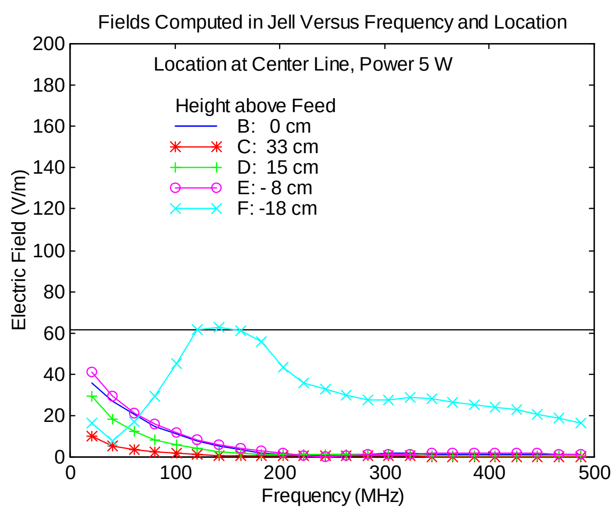


Figure 69. Fields computed in a jell around which vest antenna has been placed.

MAKING THE ANTENNA MORE RUGGED

One of the factors that has made the vest antenna fragile is the feed area. Every antenna has a single point of failure. This is the feed. If the feed is broken, there is no longer an antenna. Thus, making the feed less vulnerable to breaking would go far towards making the entire antenna more rugged. Several times the capacitor in series with the feed has broken. Since the FLECTRON has such a low melting point, copper tape has been used at points in which leads must be soldered. The copper tape sometimes rips the FLECTRON. Kinks develop in other places. The region from the connector at the bottom of the vest to the feed region in the gap is another source. A semi-rigid cable has always been used. The walking or other movement of the wearer causes stress at the soldering points. Either the solder breaks or the copper tape used at the soldering point tears. Both have occurred often in ordinary wear.

We encased the feed region in a silicon type of material called “goop.” This substance comes out of the tube as a liquid. After setting for 24 hours, the material hardens to a solid encasement. Very little can happen to the feed region inside the goop. The capacitor within the goop is probably invulnerable to all but a bullet fired directly at the feed. The whole antenna was less vulnerable.

Instead of using copper tape sewn to the FLECTRON to provide places for soldering, we used snaps that attached firmly to the material. The places that needed to be soldered could be done so with little danger of breaking under normal wear. The soldering points were less vulnerable.

Instead of semi-rigid cable, we used flexible cable. The cable could be attached to a rigid board on the other side of the material. Since the cable was designed to flex, it was less likely to break under normal circumstances. There were no soldering points to break. The shield part of the cable was soldered to the snap connector.

Figure 70 shows the design for a ruggedized feed before the application of goop. Snaps were soldered to the conducting center or to the shielding part of the flexible cable. This figure shows a return circuit shorting the two snaps on opposite sides of the gap. When attached to a network analyzer, the impedance showed the effect of the goop or of any other factor affecting the feed after attempts to disrupt it. Figure 71 shows the sample feed after the application of goop. The feed was much less vulnerable.

Canvas has been used as the backing material for the antenna. Canvas is cheap and tough. Unfortunately, the material absorbs water readily. This absorption leads to shorting of the antenna if the wearer sweats heavily.

Huber textiles sent SSC San Diego samples of urethane. The material was impervious to water. Water beads and rolls off the material without being absorbed. We made the backing material of urethane so that the FLECTRON was not exposed to moisture from the wearer.

If the FLECTRON is exposed to water, a slow-acting chemical reaction begins. The wet areas turn green. An ohmmeter applied to various regions in which water has been applied show that the material is an insulator. The FLECTRON could no longer be used as the material for an antenna. Applying Kiwi spray for waterproofing of fabrics greatly slowed this reaction. One day after the Kiwi spray was applied, the sample was dipped into a 1% salt water mixture. As a control, an untreated sample was also dipped into the solution. Within 1 day of the dipping, the untreated material became an insulator. Ten days after the dipping, the treated material was still conducting. There were some splotches of green, however, even on the treated regions.

The use of the Kiwi spray is just an example. There is undoubtedly some sort of liquid into which the FLECTRON could be dipped. The material is probably a type of plastic that solidifies and makes the material impervious to water. This would also make the FLECTRON so that air could not go through it. The wearer would become very hot. Holes can be added to the FLECTRON. The addition of the holes would affect the impedance and the matching. The holes would also admit more field and possibly increase the radiation hazard. Once a detailed engineering study is made, a solution that allows air to flow through the holes while maintaining the conducting material as waterproof could be found.

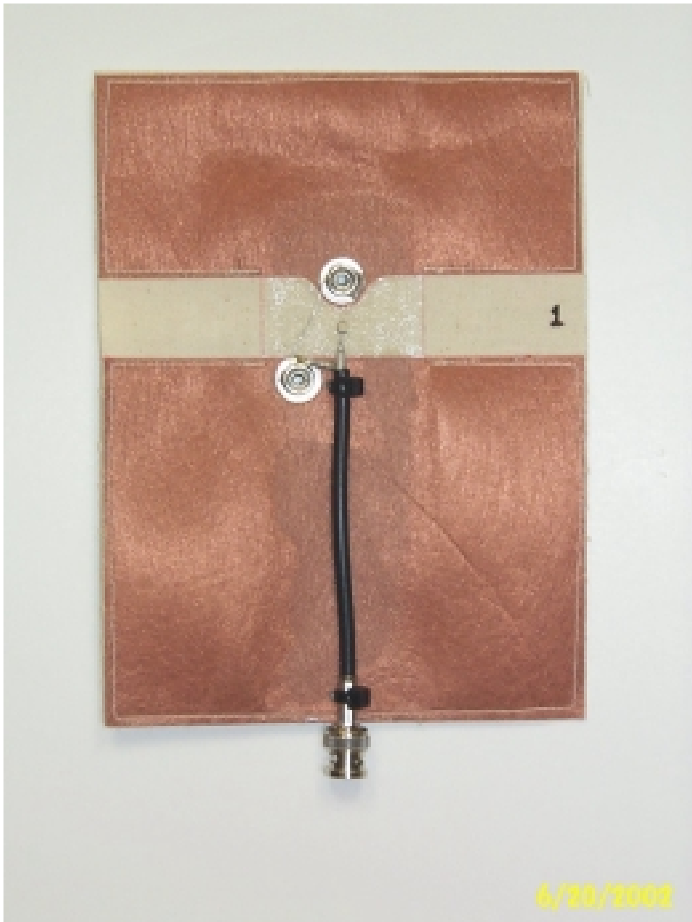


Figure 70. Sample feed after using snaps for providing soldering points and flexible cable.

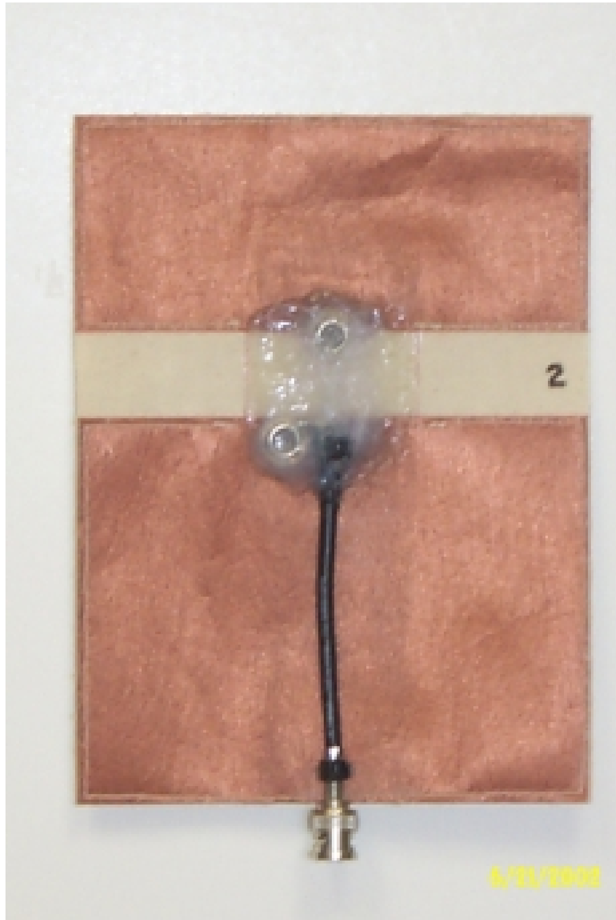


Figure 71. Sample feed after applying goop
to make whole antenna less vulnerable.
A shorting strip between the snaps allowed
a network analyzer to determine integrity of
feed after attempts were made to disrupt it.

THE WAY AHEAD

One of the more significant events of the COMWIN project occurred in late May 2001. Capt. Koby Moran, program manager for the Integrated Infantry Combat System of the Marine Corps Systems Command agreed to become a transition sponsor for the COMWIN vest antenna. This event made it possible for the vest antenna to become a military system. The vest antenna could possibly become part of the standard uniform of the marine.

Many events must occur for the COMWIN antenna to be part of a uniform widely issued to the military. First, deficiencies must be corrected. As shown in the test at Fort Huachuca, the gain of the vest when worn is bad in the UHF frequency range. To be truly broadband, changes must be made in the antenna. These changes must be done carefully. The influence of the impedance of the person is necessary for the matching of the antenna. The antenna must not be completely decoupled from the person.

Second, development must continue. There must be a concerted engineering effort to solve many problems simultaneously. These problems include increasing the antenna's durability, efficiency, and comfort. These cannot be solved individually. The solution of one will affect the others.

Third, other customers must be found. Firemen are an obvious market. The vest antenna under the protective gear would probably be more convenient than carrying a radio with an antenna. There would be no antennas to catch on low-hanging fixtures or doorways. An ultra-broadband radio and antenna system would possibly be lifesaving. Newspaper articles have described the chaos that doomed the firemen at the World Trade Center collapse. The booster on top of the towers failed. The firemen could not communicate with their commanders outside. The commanders could not tell the men inside that the towers were about to collapse. A broadband antenna could be helpful. Buildings restrict communications. If one frequency fails to get through, a broadband system would provide others, one of which would likely go through the lattice of steel and plaster.

The largest customer could be the U.S. Army. The Army is under the same ORD of the JTRS. Next year, a vendor will be found to manufacture the hand-held JTR. The Army will need a wearable antenna that provides ultra-wideband communications. The purchase of two sets of helmet and vest antennas and their testing at Fort Huachuca has already demonstrated interest in the technology.

There are tentative plans to have an exercise with U.S. Marines using the COMWIN vest antenna during the summer of 2003. Approximately 30 Marines equipped with the antenna would show the use of the device in executing military maneuvers. Several events must happen before this exercise can take place. First, the COMWIN vest antenna must pass the radiation hazard test held on 10 September 2002. Wayne Hammer attended the test. He has the authority to certify sites and equipment as safe under specified conditions. Since the experiments of late July 2002 went well, there is no reason to expect the next ones to be any different. Second, a set of protocols must be developed by consultation with the Human Factors Committee. This consultation can only be done after certification. The protocols will describe the conditions under which the equipment is safe and will inform the users of any potential hazards. Finally, an engineered design and manufacturing techniques must be developed. The COMWIN has a simple design. The FLECTRON is mass-produced by an American company. The techniques used do not involve high skills. The design that corrects the deficiencies described above will probably be more complex and involve higher skills for manufacture. These issues must be resolved if the COMWIN antenna is to be the system for future military communications for the dismounted marine or soldier.

CONCLUSIONS

The COMWIN antenna system began in FY 1999 in response to the ORD of the JTRS. The Marines realized they did not have an antenna suitable for the requirements of ultra-wideband communications of the ORD. The second goal of making the radio operator indistinguishable from other marines quickly followed. The COMWIN satisfies both goals by being hidden by the uniform and by having a VSWR of less than 3:1 for all frequencies specified by the ORD. In the 3 years of the project, the COMWIN has progressed to an integrated system that is light, simple, and fairly inexpensive.

Work remains to be done. Although the initial results are extremely promising, the COMWIN vest antenna must pass the radiation hazard certification test before the project can advance. The COMWIN vest antenna must correct the deficiency of insufficient gain when worn especially in the UHF band. Finally, the COMWIN antenna must find customers such as the U.S. Army interested in this technology.

REFERENCES

Abramo, Robert, Richard Adams, Frank V. Canez, and Howard Pace. 2000. "Fabrication and Testing of the COMWIN Vest Antenna," presented at MILCOM 2000 Conference. October. Los Angeles, CA.

Adams, R. C., C. P. Haglind, H. Pace, J. Lebaric, R. Adler, T. M. Gainor, and A. T. Tan, "Fiscal Year 1999 Wideband Antenna Feasibility Study: Man-Carried Ultra Wideband Antenna System." 1999. Technical Report 1808 (Nov). SPAWAR Systems Center, San Diego, CA.

Adams, R. C., R. S. Abramo, J. L. Parra, and J. F. Moore. 2000. "COMWIN Antenna System Fiscal Year 2000 Report." Technical Report 1836 (Sep). SPAWAR Systems Center, San Diego, CA.

Adams, R. C., R. S. Abramo, and D. W. Von Mueller. 2001. "COMWIN Antenna Project: Fiscal Year 2001 Final Report." Technical Report 1866 (Aug). SPAWAR Systems Center, San Diego, CA.

Chou, C. K., G. W. Chen, A. W. Guy, and K. H. Luk. 1984. "Formulas for Preparing Phantom Muscle Tissue at Various Radio Frequencies," *Bioelectromagnetics*, 1984, vol.. 5, p. 435.

Chou, C. K., H. Bassen, J. Osepchuk, Q. Balzano, R. Petersen, M. Meltz, R. Cleveland, J. C. Lin, and L. Heynick. 1996. "Radio Frequency Electromagnetic Exposure: Tutorial Review on Experimental Dosimetry," *Bioelectromagnetics*, 1996, vol. 17, p. 195.

Department of Defense. 1995. "PEL (Permissible Exposure Limits) for Controlled Environments." DODI 6055.11 (February 21).

Department of the Navy. 1999. OPNAVINST 5100.23E (15 Jan). Chapter 22, "Non-Ionizing Radiation." Washington, DC.

IEEE (Institute of Electrical and Electronics Engineers). 1991. "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz," IEEE C95.1-1991. Piscataway, NJ

Leonard, N. B., K. R. Foster, and T. W. Athey. 1984. "Thermal Properties of Tissue Equivalent Phantom Materials," *IEEE Transactions on Biomedical Engineering*, vol. BME-31, no. 7 (Jul), p. 533.

Mini-Circuits. 1997. "RF/IF Designer's Handbook." Brooklyn, NY.

Olsen, Richard G. 1982. "Far-Field Dosimetric Measurements in a Full-Sized Man Model at 2.0 GHz," *Bioelectromagnetics*, vol. 3, p. 433.

Operational Requirements Document (ORD) for Joint Tactical Radio (JTR). 1998. March 23. URL: http://www.fas.org/man/dod-101/sys/land/docs/jtr23_mar.htm.

Thomas, T. 1999. "The Battle of Grozny: Deadly Classroom for Urban Combat," *Parameters*, vol. 29 (Summer), pp. 87-102

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